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Selected Papers from Global '95 Concerning Plutonium

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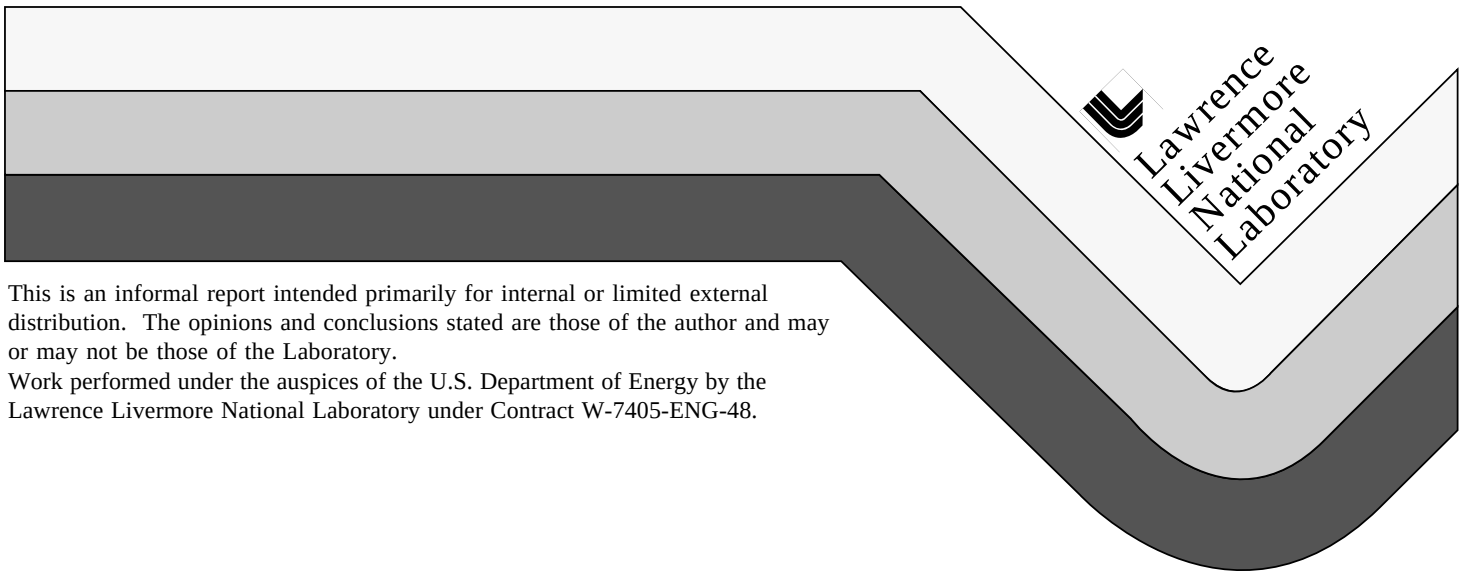

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Preface

This report contains selected papers from the Global '95 Conference, "Evaluation of Emerging Nuclear Fuel Cycle Systems," held in Versailles September 11 through 14, 1995. The conference was sponsored by the French Section of the American Nuclear Society and the Fuel Cycle and Waste Management Division. The meeting was organized in cooperation with the International Atomic Energy Association (IAEA) and co-sponsored by the French Nuclear Society (SFEN), the OECD Nuclear Energy Agency (OECD/NEA), the Atomic Energy Society of Japan (AESJ), the Kurchatov Institute, the Russian Nuclear Society, and others.

The papers in **Part I** of this report are from the "Benefits and Risks of Reprocessing" Sessions. At Global '93, in Seattle, there seemed to be an unquestioned assumption that nuclear power in general, and reprocessing (recycling of plutonium) in particular, are essential for the world's energy needs. This assumption is disputed by those who believe that reprocessing poses grave risks for the proliferation of nuclear weapons, and is not economical. It was my intent to have both sides of the proliferation and economic questions presented in these sessions in order to examine the reasons for this difference in positions. Co-chairing these sessions with me were: L. F. Durret, COGEMA, France (Session 7); and R. Baschwitz, IAEA, Austria (Session 8). The authors in these sessions were challenged to address the economic and proliferation benefits and risks resulting from reprocessing and recycling of plutonium. Technical, safety, and ecological issues were not called into question, although benefits in conservation of resources and the management of nuclear waste have been asserted by proponents of reprocessing/recycling.

After our sessions the basic disagreements remained but I think that each side has a better understanding and appreciation of the other side's view. Although economics of plutonium use (recycling) were debated, I think that most people at the session, and at the conference, concluded that the economic viability will be determined by the marketplace in the long run. In the meantime some countries are pursuing the use of plutonium for reasons of energy security and technology leverage in the future. What remains as the critical unanswered question (and a challenge for future work) is "What are the relative impacts, on nuclear proliferation, of safeguarded reprocessing/recycling versus direct disposal of spent fuel?"

I believe that it is essential to continue this dialogue, focusing on this proliferation question. It seems to me that there is a basic problem or paradox in that there are certain countries that may, or appear to, pose a proliferation risk (Iraq is a case in point), but the Non-Proliferation Treaty (NPT) guarantees the sharing of nuclear power technology. Accepting that reprocessing/recycling in countries such as France and the UK does not present a security or direct proliferation risk, how can reprocessing/recycling technology be denied to other NPT members? Perhaps the development and adoption of fuel cycles procedures that are more proliferation-

resistant could aid the solution to this problem. These could possibly include reprocessing and recycling of plutonium that does not result in a separated product, and collocation of facilities to minimize transportation. The adoption of such fuel cycles and procedures could allow more flexible diplomatic and institutional responses to emerging nuclear power programs.

As well as this classic proliferation concern, the new "proliferation" threat that a terrorist (possibly subnational) group will obtain or construct a nuclear weapon is demanding attention. Although highly enriched uranium may be more attractive than plutonium for a terrorist, we are focusing on plutonium issues. The question here becomes one of guarantying the security, of plutonium, whether recycled, or in spent fuel. Vulnerabilities, threats, and countermeasures for both open and closed fuel cycles need to be analyzed from various perspectives. It is important to investigate these issues now because today's decisions, or lack thereof, will affect the future direction of nuclear power, and hence the future security and environment of the world.

Many more papers were solicited and submitted for Global '95 than could be accommodated in the oral sessions. There was a real effort by the organizing committee to accept all worthy papers and not to relegate poster papers to a second-class status. To this end the poster papers were summarized in a plenary session, and presented alone, when no other sessions were in progress. **Part II** consists of some of the more interesting poster papers that relate to the use of plutonium for power generation.

Part III contains three papers on the topic of management and disposition of plutonium from retired nuclear weapons. This is an important topic in its own right, first because of the need to protect and account for the plutonium, second because there is still concern about reconstitution of stockpiles of nuclear weapons (vertical proliferation), and finally this topic takes on significance for the question of reprocessing and recycle because of the perception that a choice of disposition option will influence the future use, or lack of use, of plutonium in the U.S.

Finally, it should be noted that some of the papers contained in this report were not available in time to be published in the Global '95 conference proceedings. Also, some of these papers have been updated since the conference. A list of authors is presented in the Appendix so that the reader can communicate with them directly.

Acknowledgments

I wish to thank the organizers of Global '95, especially Massimo Salvatores, Chairman of the Technical Organizing Committee, for making the "Benefits and Risks of Reprocessing" Sessions possible; the session co-chairs, L. F. Durret and R. Baschwitz, for their invaluable help in managing the sessions; and the authors, of both oral and poster papers, for their professional efforts to analyze the difficult

issues surrounding the use of plutonium for nuclear power. I would also like to thank my colleagues who provided comments and suggestions on this document. In particular I would like to thank Arthur de Montalembert, Bill Hannum, Jim Hassberger, Robert Baschwitz, Carl Walter, Massimo Salvatores, and Maurice Bryson for their very useful input. Finally, I would like to thank Karen Kimball, Edie Alton, Merry O'Brien, Rita Gagetta, Carolin Middleton, and especially Cynthia Talaber for their efforts in producing this report.

William G. Sutcliffe
August 1996

Part I

An Evolutionary Approach to Fission Power

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Abstract

There will be no economic or resource reason to separate plutonium from spent reactor fuel for at least 100 years. Reactor-grade plutonium is as weapons-useable as weapon-grade plutonium. Plutonium in spent nuclear fuel is much more secure against theft than separated plutonium. Reprocessing will not significantly accelerate ultimate waste disposal during the next 50 years since both spent fuel and vitrified high-level waste will be kept in interim retrievable storage for at least that long. There should therefore be a global moratorium on further plutonium separation.

Persistence of the Once-Through Fuel Cycle

It has been recognized from the beginning of the nuclear era that, if fission is to be a major long-term source of energy for humanity, it will be necessary to shift over time from a primary dependence for fuel from U-235 to artificial fissile isotopes bred from more abundant U-238 or Th-232. However, early projections of the quantity of uranium in high-grade ore deposits and of the rate of fission-power-capacity growth turned out to be gross underestimates and gross overestimates respectively.

As a result, the current stage of fission power evolution, in which the simple once-through fuel cycle is the most economical, can be expected to last at least several more decades—even with a resumption of robust nuclear-power capacity growth. In the most recent 1994 OECD analysis, the range for long-term costs for spent-fuel encapsulation and disposal was given as 140-670 ECU/kg, while the range for long-term cost of reprocessing plus vitrified high-level waste disposal was given as 630-1300 ECU/kg.[1] Plutonium-recycle advocates have emphasized the fact that the two ranges overlap but the overlap is small.

In the future, the price of uranium will increase, shifting the economic advantage toward reprocessing and recycle, but the shift cannot be expected to be dramatic. If we assume that 8.4 kg of natural uranium are required to produce 1 kg of LEU (4.4% enrichment, 0.2% tails) and if recycle of the uranium and plutonium recovered by reprocessing reduces this requirement by 25 percent, then an increase in the price of natural uranium to $130/kg from its current price of about $25/kg would increase the relative cost of the LEU fuel cycle by only $220/kg.

According to estimates in the 1993 OECD/NEA uranium survey, however, the world resource of uranium, recoverable at a cost of $130/kg or in other comparably high-grade ores whose recovery cost has not yet been estimated, is about 20 million tons.[2] Beyond these conventional resources are huge unconventional resources. Vast deposits of uranium in sandstone have recently been identified in the U.S., Australia, and Central Asia which could be obtained through in situ leaching at costs estimated at about $50 per kilogram U. Especially arresting are gigantic "roll-fronts" in sandstone deposits in the steppes of Central Asia, in Kazakhstan and Uzbekhstan, which may contain tens of millions of tonnes of uranium.[3] Even given the "high-growth, high-nuclear" scenario put forward in 1992 by the International Panel on Climate Change (IPCC), which would have the world's nuclear capacity increase roughly linearly to 1250 GWe in 2050 and 2700 in 2100,[4] the cumulative consumption of uranium on a once-through LWR fuel cycle would be only 5 million tonnes by 2050, 5.3 million tonnes by 2050, and 17 million tonnes by 2100.[5]

It may be argued that only about 10 percent of the world's estimated low-cost uranium—about 2.1 million tonnes—is in the Reasonably Assured Resources (RAR) category. However, the global rate of uranium consumption is projected to rise to only 75,000 tonnes/yr by the year 2010. At that rate, the current Reasonably Assured Resources will last for about 30 years. At the current spot price of about $25/kg-U there is little economic incentive to make the investments required to upgrade the status of the uranium in the less well explored or undiscovered deposits, except for very high-grade deposits (which are still being found[6]). If more certainty were required, it could be obtained for much lower cost than the many billions of dollars that were wasted in premature efforts to commercialize plutonium breeder reactors.

Of course, reprocessing was originally justified not by plutonium recycle in LWRs but rather by the need to obtain startup plutonium for a second generation of nuclear reactors: fast-neutron plutonium-breeder reactors. However, the price of uranium would have to rise much higher for breeder reactors to become economic. Sixteen years ago, when two Princeton colleagues and I carried out an economic comparison of plutonium-breeder reactors with a once-through LWR and advanced-converter-reactor fuel cycles, we found that, even for a capital cost for the sodium-cooled breeder reactor only 25 percent higher than for the LWR, it would not be competitive with an LWR operating on a high-burnup once-through fuel cycle until the price of uranium climbed to about $400/kg ($60/pound U_3O_8 in 1976$).[7] Even at that price, uranium would account for only about 14 percent of the cost of electricity from an LWR.[8]

Persistence of Reprocessing

Before the long-term economic viability of the once-through fuel cycle became as clear as it is today, some countries launched major reprocessing programs in anticipation of the deployment of plutonium breeder reactors. After 1974, when

India exploded a "peaceful nuclear device" using plutonium separated under this pretext, these reprocessing programs became a source of international controversy. The U.S. adopted an anti-reprocessing position but France, Britain, Russia, Japan, and India maintained their commitments to reprocessing. Why?

In the case of Britain and France, the answer must lie in good part in the foreign exchange that they have been able to earn by reprocessing the spent fuel of other countries—especially Japan and Germany, whose commitments to reprocessing was motivated more by environmental politics than economics. Anti-nuclear activists in Germany and Japan argued that nuclear power reactors in their countries should be shut down because the operators had not found a solution to the spent fuel disposal problem. The operators were then required by their governments to enter into reprocessing contracts with Britain and France to demonstrate that they did have a solution to this problem.

Even at their final high costs, the reprocessing contracts were not a permanent solution to the German and Japanese utilities' problems, however, because they specified that the plutonium and glassified high-level waste would be returned to the country of origin a few years after reprocessing. Return shipments from France to Japan are now beginning and are causing considerable international controversy and embarrassment to the Japanese utilities. And German utilities have been blocked by their environmentalists from bringing into operation the plant that they built in Hesse to produce MOX fuel out of the plutonium separated from their spent fuel in Britain and France.

The German government has therefore recently given its utilities the option of not reprocessing their spent nuclear fuel and they have begun to cancel reprocessing contracts beyond the prepaid contracts with which they helped to finance the construction of Britain and France's commercial reprocessing plants. Instead, they are beginning to store their spent fuel at two central interim storage sites in Germany while they look at long-term disposal options. The Japanese utilities have decided not to enter into additional reprocessing contracts with Britain and France but instead to build their own reprocessing plant at Rokkashio. However, the estimated cost for completing that plant has now become astronomical—about $20 billion—and the utilities would like to abandon it in favor of interim storage. The problem is that they have not been able to find any local government willing to host an interim storage site because of the suspicion that the interim storage will become permanent storage. Therefore, while not abandoning the construction of their first reprocessing plant, the Japanese utilities are building more spent-fuel storage capacity at the site and have postponed the construction of a second reprocessing plant.

Given the prospective decline in their foreign reprocessing business, the British and French governments are beginning to force their own utilities to make larger commitments to reprocessing. At the same time, Russia's Ministry of Atomic Energy (MinAtom), hopes to follow the lead of Britain and France and build a huge

(1500 tonnes/yr) new reprocessing plant at Krasnoyarsk-26 with foreign financing from countries such as South Korea and Taiwan. This proposal has triggered considerable resistance in Russia's environmental community, which is concerned that the Ministry is trying to make its reprocessing contracts more attractive by offering to keep foreign high-level waste—something which MinAtom, in fact, recently did to obtain a Hungarian reprocessing contract for its existing small reprocessing plant at Chelyabinsk-65. In all three countries, the political imperative is to maintain the employment of work forces in government-owned companies. This is a familiar phenomenon in the United States, where weapons are manufactured that are not needed.

Interim Spent Fuel Storage

Given that the economic value of the plutonium and uranium in spent fuel does not justify the cost of reprocessing at today's prices of uranium and separative work, reprocessing advocates have adopted the argument of the anti-nuclear movement that it would be irresponsible to dispose of plutonium and other long-lived transuranic isotopes underground. It is also argued that burial of spent fuel would create "plutonium mines" which could ease access to nuclear weapons materials in the future.

However, the countries that have adopted a once-through fuel cycle, are not, in fact, yet disposing their spent fuel irreversibly underground. Because of the concerns of their environmental communities, they are moving forward very slowly. Their spent fuel is typically expected to stay in interim or retrievable storage for at least 50 years.

Nor are the countries that are reprocessing commercially rushing to dispose of the resulting vitrified high-level waste (HLW) irreversibly underground. British Nuclear Fuel Limited has, for example, contracted for the storage of Scottish Nuclear's spent fuel and/or the residual high-level waste "until the year 2086 or until a suitable repository is available."[9] Environmentalists have not been persuaded that it is less hazardous to place vitrified HLW than spent fuel underground. And they may be right—given the fact that the long-lived fission products in the HLW: Tc-99 (0.2-million year half-life), I-129 (17 million years); and Cs-135 (3 million years) are much more soluble and therefore more mobile with ground water, through the food chain and finally into the human body, than plutonium oxide.[10]

Much of the plutonium that is being recovered by commercial reprocessing is also going into long-term interim storage. All of the more than 50 tonnes of plutonium that has been separated by Britain from Magnox fuel over the past 30 years is in long-term interim storage at Sellafield. Presumably the plutonium that is to be separated from the spent fuel of Britain's AGRs will be stored there as well. Similarly, all the 30 tonnes of LWR plutonium that has been recovered at Russia's Mayak reprocessing plant is in storage there. A stockpile of foreign plutonium is

accumulating in Britain and France as well—because the rate of separation of this plutonium exceeds by far world capacity to fabricate the plutonium into MOX and because some countries—most notably Japan—have not yet licensed sufficient reactor capacity to absorb the MOX as fast as it is produced.

And then, of course, there is the 150 tonnes or so of surplus plutonium from dismantled U.S. and Russian nuclear warheads accumulating in interim storage as well.

Given that reprocessing is not accelerating the permanent disposal of high-level waste and is exacerbating the problem of excess separated plutonium, it would appear to make sense to reduce the rate of reprocessing at least until the huge surplus of separated plutonium is dealt with and the debate over the relative risks of underground disposal of spent fuel and glassified high-level waste are decided.

The absurdity of reprocessing under current conditions can be illustrated by a suggestion that was made to Britain when it was debating the operation of the new THORP reprocessing plant. It was noted that the prepaid reprocessing contracts with which Britain had built THORP could be satisfied without turning the plant on. Instead of turning the foreign spent fuel into separated plutonium and high-level waste, Britain could simply store the foreign spent fuel and send its foreign customers separated plutonium and HLW from its own stocks. It would thereby, in effect, have converted the unstable metal Magnox fuel which it had reprocessed into a much smaller tonnage of stable oxide fuel, creating for itself the option of direct disposal, while using the remaining funds owed under the reprocessing contracts to mothball the THORP plant and employ its workforce on some more useful activity.

Unfortunately, this alternative was not considered seriously. The British and the Japanese establishments were too committed to winning the fight to open THORP—and the Rokkashio plant thereafter.

Separated Plutonium and the Danger of Nuclear Terrorism

Why do people like myself, who work primarily on nuclear arms control and nonproliferation policy issues, concern themselves about national choices of nuclear fuel cycle for nuclear power? The main reason today is that separated plutonium is much easier to steal than plutonium in spent nuclear fuel. This is illustrated by the situation in Russia, where the stresses of a very difficult economic and political transition have resulted in the potential for large-scale theft of separated plutonium and highly-enriched uranium.

To illustrate the dangers of long-term stockpiling of separated plutonium, consider the fact that, at the Mayak reprocessing plant in the Urals, 30,000 kg of reactor-grade plutonium are stored in about 12,000 coffee-pot-sized containers in an ordinary building. The plutonium in two to three of these containers would be sufficient to make a nuclear explosive. The gamma and neutron dose rates from the

containers are low enough so that they could be handled by terrorists without a significant amount of shielding.

In contrast, if one were to try to steal the same amount of plutonium in the spent fuel from a pressurized water reactor, it would be necessary first to steal a large highly-radioactive fuel assembly weighing hundreds of kilograms, which would give anyone standing nearby without shielding a lethal dose of radiation in on the order of ten minutes.[11] In order to transport it, it would be necessary to put it into a heavily shielded cask weighing tens of tons. And recovering the plutonium from the fuel assembly would require a facility that could chop up the fuel, dissolve it, and chemically recover the plutonium from the solution—all remotely behind heavy shielding—i.e., a reprocessing facility. Only after all that would the plutonium become as accessible to black-marketeers and terrorists as already-separated plutonium.

Currently, theft by black-marketeers of plutonium is not a major concern in the U.S., Western Europe or Japan. However, commercial reprocessing in Western Europe is used to justify reprocessing in Russia, and commercial reprocessing in Japan was used to justify reprocessing in North Korea—and might in the future be used to justify reprocessing in South Korea and China. In the past, plans for commercial reprocessing in the U.S. and Western Europe were used to justify reprocessing in India and proposals for reprocessing in Argentina, Brazil, South Korea, Pakistan and Taiwan—all of which were interested in acquiring nuclear weapons at the time. In the future, another reprocessing country will probably undergo a convulsion such as that currently gripping Russia. Where are the benefits from reprocessing that justify all these security risks? The risk-benefit balance may be different 50 or 100 years hence but that does not justify reprocessing today.

The Weapons-Usability of Reactor-Grade Plutonium

One of the reasons given by reprocessing advocates for their lack of concern about the potential for nuclear proliferation or nuclear terrorism resulting from the separation of plutonium from spent LWR fuel is that reactor-grade plutonium is not weapons useable. Thus, recently, in the September 1994 Financial Times Forum on "Crucial Issues in Managing the Fuel Cycle," Cogema Vice President, Jean-Pierre Rougeau (at that time also Chairman of the French Nuclear Energy Society) stated that: "reactor-grade plutonium is not realistically a potential weapons material . . . it is—practically speaking—virtually impossible to convert reactor-grade plutonium to military use."

Such statements are made despite briefings to the contrary by U.S. weapons designers for almost 20 years. Indeed, this intransigence was evident from the very beginning. One Los Alamos weapons designer told me that the response from leaders of the French nuclear-energy establishment to the first U.S. briefing in 1977 was, "No matter what you say, our plutonium is innocent!"

Well reactor-grade plutonium is not innocent! As has been explained in detail in an authoritative unclassified publication by Carson Mark, head of the Los Alamos Theory group from 1947-1972, if reactor-grade plutonium were substituted for the weapon-grade plutonium in the 1945 Nagasaki bomb, the yield at minimum would be on the order of 1000 tons of TNT—about one thousand times the power of the explosions under the World Trade Center and outside the Federal Building in Oklahoma City.[12] The results of a comprehensive review of post-Nagasaki designs—done at the request of the National Academy of Sciences plutonium-disposition study group[13] by weapons designers at the Livermore and Los Alamos Laboratories recently was summarized in the following unclassified statement:

> "Except for high purity Pu-238, plutonium of any isotopic composition, including that in spent fuel from commercial power reactors, can be used to make a nuclear weapon that is capable of significant nuclear yield. Design and construction of any nuclear weapon is a difficult task—but is a task that can be accomplished with a level of technical sophistication and computational capability that existed in the early 1950s at the nuclear-weapons design laboratories. Examination of designs typical of 1950s nuclear weapons indicate that replacing weapons grade plutonium with plutonium of other isotopic composition could have two results: it might decrease slightly the maximum yield of the weapon, and it might reduce the probability that maximum yield would be obtained in an explosion. *However, even in extreme cases, yields on the order of kilotons would result* [emphasis added]."

That is, if a nation—or a terrorist group—can construct a nuclear weapon with weapons-grade plutonium, it can construct one with reactor-grade plutonium. For this reason, the International Atomic Energy Agency, which has been advised on this matter by international weapons experts, does not distinguish between its requirements for safeguards on weapon-grade and reactor-grade plutonium.

References

1. *The Economics of the Nuclear Fuel Cycle* (Paris: OECD/NEA, 1994), Table 5.5.
2. *Uranium: Resources, Production and Demand* (Paris: OECD/NEA, 1993). Specifically, the cumulative resource estimates (in millions of tonnes U) at recovery costs of $130/kg or less is as follows: Reasonably Assured Resources (in known deposits)—2.1; plus Estimated Additional Resources (in known deposits)—3.0; plus other known resources, mostly in the former Soviet Union, where estimation methodology is not strictly consistent with NEA/IAEA resource terminology—4.4; plus estimated additional resources in known uranium areas—6.9; plus median estimates of undiscovered resources in areas of favorable geology— 8.9; plus undiscovered resources whose cost range has not been assigned: in China—10.7; plus Mongolia—12.0; plus South Africa—

13.2; plus Australia—15.8-17.1; plus other countries—16.4-17.7; plus uranium in phosphates recoverable as a byproduct (mostly in Morocco)—23.5-24.8.

3. Thomas Neff, M.I.T., private communication, June 1995.
4. Intergovernmental Panel on Climate Change (IPCC), Scenario IS92a, high nuclear/high demand scenario. The data in the IPCC scenario are given in exajoules per year of primary energy equivalent. These were converted to installed nuclear capacity on the basis of a capacity factor of 0.75 and a conversion of 10^7 joules per Kilowatt-hour (electric).
5. An annual uranium consumption of 120 tonnes U has been assumed per GWe-yr. This is appropriate for a 75 percent capacity factor, high burnup (53 MWt-day/kgU) and enrichment tails of 0.2 percent.
6. Huge new deposits of uranium with grades up to 30% uranium have recently been found in North Saskatchewan (private communication, D.E. Anderson, General Manager, Ontario Hydro Nuclear, June 19, 1995).
7. Harold A. Feiveson, Frank von Hippel and Robert H. Williams, "Fission Power: An Evolutionary Strategy," *Science* **203** (1979), pp. 330-337.
8. The capital cost of an LWR was assumed to be about $2000/kWe in current dollars (assuming that a 1976 dollar is worth $2.50 in 1995 dollars). Today, the capital cost for a passively-safe PWR is estimated at $1850/KWe [Palo Alto, Calif: Electric Power Research Institute, Technical Assessment Guide, EPRI TR-102275-V1R7, June 1993]. Assuming a capital recovery factor of 10%, the capital charge per kWh at a 75 percent capacity factor would be 2.8 cents/KWe-hr. Operating cost is estimated at 1 cent/kWh. Fuel cycle costs, excluding the cost of uranium purchase are approximately 0.4 cents/KWh [Paris: OECD/NEA, *The Economics of the Nuclear Fuel Cycle*, 1994, Table 5.7]. The contribution of $400/kg uranium to the cost of electricity would be approximately $(400 * 7.05) /(53 MWd/kg * 0.33 * 24,000 KWh/MWd) = 0.7 cents, where 7.05 kg of natural uranium are required to produce 1 kg of 4.4% U-235 at 0.1% tails assay.
9. *Nuclear Fuel*, May 22 1995, p. 4.
10. See, e.g. Thomas H. Pigford, "Actinide Burning and Waste Disposal," in *Proceedings of the First MIT International Conference on the Next Generation of Nuclear Power Technology*, Oct. 4-5, 1990.
11. See, e.g. W.R. Lloyd, M.K. Sheaffer, and W.G. Sutcliffe, *Dose Rate Estimates from Irradiated Light-Water-Reactor Fuel Assemblies in Air* (Lawrence Livermore National Laboratory, UCRL-ID-115199, 1994).
12. Carson Mark, "The Explosive Properties of Reactor-grade Plutonium," *Science and Global Security* **4**, 1993, pp. 111-128.
13. NAS Committee on International Security and Arms Control, *Management and Disposition of Excess Weapons Plutonium* (National Academy Press, 1994), pp. 32-33.

The Policy of the United States with Respect to the Reprocessing of Spent Fuel

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Abstract

Of the last four U.S. administrations, three (the Ford, Carter and Clinton administrations) have demonstrated a marked bias against the reprocessing of spent fuel because of the alleged nuclear proliferation risks. There are signs, however, both within the Clinton administration and the Congress, that the current hostility to reprocessing may be weakening, primarily because of the urgent need to effectively dispose of the large plutonium stocks derived from weapons that must be dismantled pursuant to agreement with Russia for vast reductions in U.S. and Russian stockpiles of nuclear weapons.

Introduction

The policy of the United States with regard to the reprocessing of spent fuel has varied widely—from the initial optimism which existed during the first years of the nuclear age to the opposition of the Carter administration to the present acquiescence to its utilization in those industrialized countries which already have very advanced nuclear programs. On the other hand, the United States now opposes the use of civil plutonium in those countries which have a limited nuclear capacity, especially those which have an unstable political situation. The United States does not reprocess spent nuclear reactor fuel and stopped the production of plutonium for weapons purposes in 1988.

The Clinton administration is in the process of reviewing its non-proliferation policies, including its plutonium policy. It is now consulting with other countries which have programs for the reprocessing of spent fuel and the use of plutonium to explore means of increasing the transparency of plutonium stocks. It is also discussing the development of guidance on the storage and use of plutonium, including options for international storage and management which would be supplementary to International Atomic Energy Agency safeguards. In these discussions, the United States is emphasizing the importance of balancing the supply and demand of separated plutonium in order to avoid the accumulation of excess plutonium stocks and to reach agreement on means of limiting and finally reducing and eliminating excess separated plutonium.

The Ford and Carter Administrations

In August 1976 the U.S. Nuclear Regulatory Commission ("NRC") published the results of its environmental review of the health, safety and environmental aspects of the use of recycle plutonium in mixed oxide fuel in light water cooled reactors (NUREG-0002, "Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors—Health Safety and Environment"). This review was one of the steps taken by the NRC to enable it to make a decision as to whether the use of mixed oxide fuel should be permitted on a wide-scale basis in the United States and, if so, under what conditions.

The principal findings by the NRC staff were as follows:

The safety of reactors and fuel cycle facilities is not affected significantly by recycle of fissile materials.

Nonradiological environmental impacts resulting from recycle of fissile materials from spent fuel are slightly smaller than those from a fuel cycle that does not reclaim residual fuel values.

Plutonium recycle extends uranium resources and reduces enrichment requirements, while entailing the need for reprocessing and fuel fabrication of plutonium-containing fuels.

While there are uncertainties, wide-scale recycle has a likely economic advantage relative to a fuel cycle that does not reclaim residual fuel values.

Differences in health effects attributable to recycle provide no significant basis for selection of a fuel cycle option.

No waste management considerations were identified that would bar recycle of uranium and plutonium.

As the result of advice received from the President's Council on Environmental Quality to the effect that the environmental review was incomplete because it failed to present a detailed and comprehensive analysis of the environmental impacts of potential diversion of special nuclear materials and of alternative safeguards programs to protect the public from such a threat, the NRC decided to have prepared a supplement to its environmental impact statement that would include both an analysis of alternative safeguards programs and an overall cost-benefit balancing that took into account the safeguards factors as well as health, safety and environmental factors.

No such safeguards supplement was ever issued because President Carter placed an indefinite ban on the commercial reprocessing and recycling of plutonium

produced in U.S. nuclear power programs. Nuclear Power Policy, Statement by the President on His Decisions Following a Review of U.S. Policy, 13 Weekly Comp. Pres. Doc. 506,507 (Apr. 7, 1977). In that statement President Carter stated, inter alia:

> "The United States is deeply concerned about the consequences of the uncontrolled spread of . . . nuclear weapon capability. We can't arrest it immediately and unilaterally. We have no authority over other countries. But we believe that these risks would be vastly increased by the further spread of reprocessing capabilities of the spent nuclear fuel from which explosives can be derived.
>
> "Plutonium is especially poisonous, and, of course, enriched uranium, thorium and other chemicals or metals can be used as well.
>
> "We are now completing an extremely thorough review of our own nuclear power program. We have concluded that serious consequences can be derived from our own laxity in the handling of these materials and the spread of their use by other countries. And we believe that there is strong scientific and economic evidence that a time for a change has come.
>
> "Therefore, we will make a major change in the United States domestic nuclear energy policies and programs which I am announcing today.
>
> "We will make a concerted effort among all other countries to find better answers to the problems and risks of nuclear proliferation. And I would like to outline a few things now that we will do specifically.
>
> "First of all, we will defer indefinitely the commercial reprocessing and recycling of plutonium produced in U.S. nuclear power programs.
>
> "From my own experience, we have concluded that a viable and adequate economic nuclear program can be maintained without such reprocessing and recycling of plutonium."

What is sometimes forgotten is that the Carter ban on reprocessing was not the first such presidential ban. In fact, it had been preceded by a similar action on the part of President Ford. In his Statement on Nuclear Policy of October 28, 1976, President Ford stated, inter alia:

> "I have concluded that the reprocessing and recycling of plutonium should not proceed unless there is sound reason to conclude that the world community can effectively overcome the associated risks of proliferation. I believe that avoidance of proliferation must take precedence over economic interests . . .

> "I have decided that the United States should no longer regard reprocessing of used nuclear fuel to produce plutonium as a necessary and inevitable step in the nuclear fuel cycle, and that we should pursue reprocessing and recycling in the future only if they are found to be consistent with our international objectives . . ."
> (Nuclear Proliferation Factbook, Committee Print, 103d Congress, 2d Session. S. PRT 103-111, pp. 51-52.)

The Reagan Administration

In any event, the unjustified hostility to reprocessing shown by the Ford and Carter administrations did not continue during the Reagan administration. To the contrary, the ban on reprocessing was lifted by President Reagan. Nuclear Energy Policy, Statement Announcing a Series of Policy Initiatives, 17 Weekly Comp. Pres. Doc. 1101, 1102 (Oct. 8, 1981). In President Reagan's words: "I am lifting the indefinite ban which previous administrations placed on commercial reprocessing activities in the United States. In addition, we will pursue consistent, long-term policies concerning reprocessing of spent fuel from nuclear power reactors and eliminate regulatory impediments to commercial interest in this technology, while ensuring adequate safeguards." U.S. commercial interest in reprocessing did not develop, however, largely because of a negative perception of the economics.

The Clinton Administration

The pendulum swung back again with the advent of the Clinton administration. President Clinton has made clear his antipathy to reprocessing in the United States while at the same time professing no desire to interfere with reprocessing in Western Europe and Japan. His key words on the subject, which have proved to be controversial and somewhat ambiguous, are contained in a Fact Sheet released by the White House on September 27, 1993, Fact Sheet: Non-Proliferation and Export Control Policy:

> "The United States does not encourage the civil use of plutonium and, accordingly, does not itself engage in plutonium reprocessing for either nuclear power or nuclear explosive purposes. The United States, however, will maintain its existing commitments regarding the use of plutonium in civil nuclear programs in Western Europe and Japan."
> Nuclear Proliferation Factbook, Committee Print, 103d Congress, 2d Session, S . PRT 103- 111, p. 195.

In a decision viewed by many as a critical test of the Clinton administration's policy on reprocessing and nuclear non-proliferation, Energy Secretary Hazel O'Leary approved on January 17, 1994 a request by the Swiss government to ship spent fuel of U.S. origin to THORP in the United Kingdom for reprocessing. Her approval came notwithstanding a letter written to her by five members of the U.S. Congress expressing strong opposition to granting the Swiss request and urging the

administration to block the shipment. The letter reminded the administration of its declared non-proliferation policy, which discourages the use of plutonium for civil and military purposes. The authors of the letter professed to "see the Swiss request as an opportunity to put this policy into practice." The letter stated that, unlike U.S. nuclear cooperation agreements with Japan and EURATOM, there was no similar agreement with Switzerland and. therefore, the United States had a "clear right" to deny permission to Switzerland to transfer and reprocess the spent fuel.

There was considerable delay before the Energy Secretary approved the Swiss request. This was due to a behind-the-scenes debate within the Department of Energy as to the effectiveness of the administration's non-proliferation policy as it relates to the issue of reprocessing. Some have interpreted the Department's hesitance to approve the Swiss shipment request as an effort by the Department to delay or halt the operation of THORP. Some have also questioned whether the Clinton administration's negative attitude towards reprocessing may have made more difficult the negotiations for renewal of the U.S.-EURATOM Agreement.

The U.S. Department of Energy had to confront again the reprocessing issue in connection with an environmental review of its proposal to continue to take back U.S.-origin spent fuel from foreign research reactors. The ambiguity and ambivalence reflected in President Clinton's statement quoted above are shown again in the following paragraph found in the Department's environmental review document.

> "In the past, some individuals and groups have incorrectly asserted that the U.S. concerns with reprocessing of HEU spent nuclear fuel . . . are inconsistent with the U.S. policy of continuing to grant prior consent to Japan and Western European nations for reprocessing of power reactor spent nuclear fuel. The U.S. Government believes that the growing quantities of plutonium in international commerce do present a threat to the efforts of the United States and other countries to prevent the proliferation of nuclear weapons. In countries where material control and accounting or physical protection systems are not sufficiently rigorous, there is a risk of diversion or theft of such materials. In addition, even in countries with effective nuclear weapons nonproliferation commitments, the presence of unneeded stocks of plutonium could raise security concerns on the part of neighboring countries. Accordingly, the United States Government does not encourage the civil use of plutonium. Nevertheless, the United States is also committed to being a reliable nuclear trading partner and to avoiding interference in peaceful nuclear programs. Therefore, in Western Europe and Japan where there are well-established civil reprocessing and plutonium facilities and comprehensive nuclear weapons nonproliferation commitments, the United States will continue, in appropriate instances, to grant prior consent for reprocessing of plutonium-bearing spent fuels on a

predictable and long-term basis. Undertaking the use of U.S. consent rights to block reprocessing would lead to confrontation with key allies and would jeopardize their support for the broader U.S. nuclear weapons nonproliferation agenda."
Department of Energy's Draft Environmental Impact Statement on a Proposed Nuclear Weapon Nonproliferation Policy Concerning Foreign Research Reactor Spent Nuclear Fuel. DOE/EIS-02 1 8D, Volume I, pp. I -5- 1 -6.

Also of considerable interest is the fact that the U.S.-North Korean "Agreed Framework" concluded on October 21, 1994, placed restrictions on North Korea beyond those imposed by the Nuclear Nonproliferation Treaty by banning reprocessing of existing spent fuel and requiring the dismantling of North Korea's most sensitive nuclear facilities.

There are signs, however, that Clinton administration's policy against reprocessing may be subject to some reexamination. For example, in the Department of Energy's draft environmental impact statement relating to the U.S. take-back of foreign research reactor spent fuel, one of the options considered is overseas reprocessing, that is, encouraging and providing financial and/or logistical assistance to foreign research reactors and reprocessors to facilitate reprocessing spent nuclear fuel overseas in facilities operated under international safeguards sufficient to satisfy U.S. nuclear weapons nonproliferation concerns. Some of the factors to be considered by the Department of Energy in connection with this option are:

- an expectation that highly-enriched uranium separated during reprocessing would be blended down to low-enriched uranium for research reactors which are converting to low-enriched uranium;

- the foreign reprocessors would provide the capability to reprocess low enriched uranium as well as high-enriched uranium; and

- research reactors would be encouraged to convert to low-enriched uranium if a low-enriched uranium fuel exists or developed that will allow such operation.

More importantly, the United States is faced with the difficult and complex problem of how to dispose of the large plutonium stocks derived from weapons that must be dismantled pursuant to agreement with Russia for vast reductions in U.S. and Russian stockpiles of nuclear weapons. The U.S. Department of Energy is engaged in a thorough review of alternative strategies and intends to announce its decisions in 1996. One of the more prominent options being considered is the so-called "spent fuel option" under which plutonium would be used as once-through fuel for existing or evolutionary U.S. light-water reactors, Canadian CANDU reactors, and European or Japanese reactors already licensed for civilian plutonium.

Renewed interest in reprocessing is also being expressed in the U.S. Congress. In late April 1995, after completion of a trip to examine French and Swedish nuclear fuel management facilities, Senator Murkowski, chairman of the Senate Energy and Natural Resources Committee, announced plans to introduce legislation to help U.S. utilities wishing to send commercial spent fuel overseas for reprocessing. The senator's announcement was made in response to the lack of progress being achieved by the Department of Energy in accommodating the needs of U.S. nuclear utilities to move their spent fuel off-site.

Conclusion

There are mixed signals from both the Clinton administration and the Congress on possible modification of the current U.S. anti-reprocessing policy. The reprocessing option is definitely being considered in certain "special" situations where the need for decisive action is obvious. Foremost among these is the need to take effective action to dispose of the large plutonium stocks derived from dismantled U.S. weapons. It is unlikely, however, that there will be a general retreat by the Clinton administration from its current hostility to commercial reprocessing. In fact, it is by no means assured that even in the "special" situations, it is the reprocessing option that will be selected. Nonetheless, the current political environment has changed dramatically with the last Congressional elections and the anti-nuclear groups and the so-called anti-proliferation groups are clearly less influential than they were before the elections. In short, there are grounds for hope that the current bankrupt U.S. anti-reprocessing policy may be modified to some extent.

Why Recycle?

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Abstract

Many factors need to be taken into account when deciding on the type of fuel cycle and treatment of spent fuel most suited to a utility's circumstances. This paper reviews these factors and considers especially the factors favouring recycle of separated irradiated Uranium and Plutonium.

Introduction

Recycling of Uranium and Plutonium has now a considerable "track record." In the UK some 15,000teU of uranium has been refabricated into fuel for AGRs and fabrication of mixed oxide fuels has been undertaken since the early 1960s. Elsewhere in the world several hundred tonnes of MOX have been manufactured and loaded to light water reactors. The technology for fabricating both MOX and recycled uranium fuel is well established and has been described elsewhere. Sufficient irradiation experience has been gained to give utilities confidence that fuels from recycled materials perform satisfactorily compared with fuels made from fresh uranium. Given that generic cost studies have not in general identified significant cost differences between direct disposal and reprocessing with recycle, this paper concentrates on and explores the other considerations which need to be taken account of in selecting spent fuel cycle options.

What then are the non economic influences on decisions relating to the fuel cycle and spent fuel management? These fall broadly into the following categories:

environmental
conservation
strategic
political
risk

This paper will explore each of these broad areas and illustrate how these factors may influence the decision on which spent fuel management option to select.

Environmental Factors

In most advanced industrialised nations environmental consciousness has been developing strongly over the last 20 years and is now a considerable driving force in many decisions which would formerly be made purely on cost grounds.

Disposal of waste nuclear materials, while small in volume compared with wastes arising from other energy forms, is the subject of much environmental interest. For nuclear energy, comparisons of the way in which different spent fuel management strategies affect the volume and radioactivity of wastes for disposal have shown that there is considerable advantage in a reprocessing and MOX fuel recycle strategy, compared with a direct disposal strategy.

Total waste arisings are lower for the recycle strategy.

The arisings of mine tailings, which dominate the totals, are lower in the MOX recycle scenario reflecting the reduced requirement for uranium fuel.

The volume of heat generating long lived waste is about a factor 10 lower in the recycle scenario.

In addition to these effects, the separation from spent fuel of plutonium and uranium reduces the relatively long lived isotope content of the materials for disposal, and recycling in reactors converts the plutonium into short lived fission products. Thus overall when longer timescales are examined an overall reduction in the radioactivity of disposed wastes of a few percent of that involved in direct disposal in early years to over 30% in the medium to long term (over say 10,000 years) can be shown.

A way of comparing waste forms from this viewpoint is based on the concept of "radiological toxic potential" and this methodology is increasingly gaining acceptance as a basis for comparison of the merits of alternative strategies. Briefly the toxic potential is a way of relating the biological effect on man of a radionuclide in a way such that the combined effect of many nuclides can be simply represented; it is in effect the volume of water into which the substance would need to be dispersed so that the water would be considered safe to drink. For periods of integration over 500 years, the integrated toxic potential for wastes arising from a reprocessing and recycle strategy are lower than for direct disposal, and for integration periods of over 100,000 years it is 35% lower. Because it is relatively straightforward to design engineered barriers to contain wastes in the short term, it is the long lived radionuclides which are of more significance when comparing the environmental impact of alternative disposal strategies.

Probably the most significant effect of adopting recycling is the reduction of mining of new uranium. This reduces a number of factors associated with mining such as the disposal of spoil heaps, the environmental pollution of ground water from mining activities, the exposure of miners to hazards of mining (physical injury, long term health effects dust etc., in addition to radiological effects).

Therefore, in summary, strategy involving reprocessing and recycle of uranium/plutonium has environmental advantage over direct disposal by reducing

total waste volume, reducing the "toxic potential" of the wastes to be disposed and reduces exposure to conventional and radiological hazard associated with mining.

Conservation of Resources

During the early phases of industrialisation little heed was taken of the need for conservation of resources. Over the last couple of decades the finite size of the earth's resources has been increasingly recognised. Just as the western world's energy resource reserves are now also recognised as having a limited life (at least in economic terms) key minerals are now also recognised as having limited availability. The role which nuclear power can play in conserving fossil fuel resources has been much discussed over the years. Uranium and Plutonium recycle in LWRs can increase there energy extraction potential by up to 30%.

Thus from a conservation of resources viewpoint, the implementation of recycling technology has merit. In the short term this will involve the recycling of Pu and U in Light Water Reactors (being the most abundant design of reactor world wide). Much higher energy returns for a given amount of mined uranium can be realised by use in fast reactor systems but it is generally accepted that commercial application of fast reactor technology will not take place until the second or third decade of the next century at the earliest.

While it is not the aim of this paper to rehearse the factors favouring reprocessing in any depth, the argument presented assumes that prior decisions have been made to choose this spent fuel management option. Perhaps a brief mention of the key reasons why the reprocessing option is taken is relevant.

It is a technology which has been demonstrated on an industrial scale and, in addition to recovering valuable materials for reuse, puts the wastes into forms which are inherently more stable (i.e., resistant to leaching by ground water) and so less reliant on engineered barriers to prevent migration of radionuclides back to the human biosphere. The removal of Plutonium and other long lived actinides reduces the length of time for which the wastes remain significantly hazardous and allows the option to transform these radionuclides into less hazardous elements by burning in a reactor to produce energy.

Economic

If adopted on a wide scale, recycling will tend to stabilise the cost of new uranium supplies. It is in the nature of the world commodity markets that as the size of easily mined mineral reserves reduces and the supply/demand ratio decreases the prices of the commodity both on the spot market and for long term contracts will increase. Recycling of Pu and U in the short term will help to stabilise the world uranium price by suppressing the demand for fresh mined uranium and extend the period for which a stable low price persists given the finite size of economic reserves. Thus in strategic terms recycling will provide a way of

promoting long term stability in the world uranium market. A stable uranium market without short or long term fluctuations in price is to the benefit of utilities in planning their fuel purchasing and will tend to result in overall stable and lower energy prices to users/customers.

While the premise of this paper is that at the present time the economics of various fuel cycle options is not the principal factor influencing decision making and generic studies such as the recent OECD/NEA report conclude that cost differences between fuel cycle strategies are not significant compared with the sensitivity of cost to basic modeling assumptions. Economics are not the only factor to be considered in decision making.

Strategic Policy Considerations

Energy independence is recognised by many nations as an important strategic consideration. The vulnerability of nations without domestic sources of energy was exemplified in the oil crisis of the 1970's where a group of producers managed the world oil price by limiting production. Although in time the higher prevailing world price stimulated exploration and introduced new sources of supply so that in the longer term oil price returned to lower levels, such perturbations in availability and cost of energy had very significant effects on many nations' economies. This prompted some to seek as far as possible to insulate their national economy from such significant external influences. The ways in which this was achieved varied by included diversification of energy sources (including expansion of nuclear energy development) conservation of energy measures to reduce demand, development of technology to maximise the use of existing resources (e.g., fast reactor development). Some nations' energy policy is now dominated by the drive towards independence from imported energy sources. Thus although in some nations the debate about the mix of energy sources is dominated by market forces and cost comparisons in the short to medium term, others have taken a far longer term view in formulating their policy and strategy in this area, and at present it is these nations that have tended to favour nuclear power expansion and a comprehensive fuel cycle strategy. In summary the above examples illustrate how the political philosophy and planning horizon together with the socio-economic environment strongly influences the choice of energy mix and the type of fuel cycle strategy adopted.

The subject of use of ex military materials for fuel manufacture is explored in other papers to this conference, but for completeness a brief mention here of the option is appropriate. Fabrication of ex military plutonium and enriched uranium into fuel for light water reactors is an effective way to make these materials unusable in the military cycle. Use of these materials in this way will also enable the utilisation of depleted uranium from reprocessing and enrichment tails further reducing the demand for fresh uranium.

Risk

Economic/technical risk is a important factor in decision making. Although back end fuel cycle choices will not have the same immediate effect on the utility's costs as say the technical choices to be made on fuel design and reliability, nevertheless basing strategy on processes which have not been fully demonstrated on a commercial scale introduces a degree of commercial risk. The amount of financial provision to be made for future expenditure needs to taken into account these uncertainties. It has already been argued above that the adoption of recycling will tend to stabilise the world uranium market from significant and rapid changes in price and availability. In addition al of the processes involved in recycling have been demonstrated on an industrial scale. Reprocessing has been operated in several nations over a period of over 40 years and manufacture and irradiation of plutonium containing fuels over say 30 years. There is thus much solid experience of the operation of these processes and the technical background is well understood. The same is not the case at this time for direct disposal. The technical aspects are still under development and must be considered to represent a significant risk to this strategy. Any technical difficulties which are discovered are likely to be soluble but the cost of finding solutions cannot be estimated with any confidence and therefore provisions for future disposal costs need to be enhanced to allow for the extent of these uncertainties.

Conclusion

At the present time economic factors do not appear to be the main driver for selection of fuel cycle strategy. Cost modeling of generic cases does not produce differences which are significant compared with the changes due to variation in basic assumptions. Other factors tend to have greater influence on policy makers and these include political, socio-economic, environmental and strategic factors. Recycling of the products of reprocessing of used fuel is well established and irradiation experience is sufficient to give utilities confidence in this technology. The prospect of using recycling technology to help transfer military material into the civil cycle also exists. Spent fuel represents a potential energy resource which should not be thrown away but should rather be utilised to the maximum extent possible. It would be irresponsible to leave spent fuel as a problem to be dealt with by future generations or to dispose of such a valuable resource.

Plutonium Economics and the Civilian Nuclear Future

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Abstract

The paper describes a methodology that derives a uranium breakeven price and a breakeven year for a given set of assumptions. The uranium breakeven price signifies the price of yellowcake at which plutonium use in a given type of nuclear reactor—e.g. a light-water reactor or a faster reactor—begins to be economically competitive with a current type light-water reactor using uranium fuel and operating on the once-through mode. The breakeven year indicates when plutonium use in a given type of reactor will be economical. The paper then discusses the key factors and uncertainties that drive the economic competitiveness of plutonium use. Finally, the paper recommends what steps countries should undertake in order to have a proliferation-resistant civilian nuclear future.

Introduction

Plutonium of practically any isotopic composition is weapon-usable. A massive use of plutonium in the commerce would make separated plutonium present in many places—reprocessing plant, fabrication plant, and the storage area of the reactor site—and in transit from one place to another.[1] Even if the supply and demand of plutonium were in perfect balance, there would still be thousands or even tens of thousands of bombs worth of plutonium serving as working stock in the system. It would be difficult for the International Atomic Energy Agency or, in fact, any other agency to prevent terrorist groups from diverting the plutonium. Worse yet, while preventing subnational diversion is only difficult, preventing host country from seizure is simply not possible. Then, the key question is whether countries should still plunge into the plutonium economy in spite of the proliferation risk. The world should only consider doing so when the plutonium benefits are enormous and certain. This paper is to examine the key factors that drive the plutonium economics and to study when the use of plutonium will become economical. The paper also recommends what steps countries should undertake in order to have a proliferation-resistant civilian nuclear future.

A Plutonium Economic Model

We have developed a model to integrate the various assumptions governing the economic viability of plutonium use. The model has four modules.[2] The first module deals with the future nuclear capacity demand. One can simply use a projection made by others. This paper uses the projection made by the Nuclear

Energy Agency (NEA) of OECD and the International Atomic Energy Agency (IAEA).[3] But, since they have not projected beyond the year 2010, we assume that worldwide nuclear capacity beyond the year 2010 will grow at the same rate as the projected growth during the period 1992-2010—1.8% a year. We also add a more optimistic nuclear growth case in which the growth rate beyond the year 2010 will be twice the reference rate—3.6% a year. These projections are shown in Figure 1. The second module estimates the future uranium price over time, when plutonium is not used. The price is determined by comparing the uranium supply and the demand for a given nuclear capacity projection determined in module 1. The supply is based on the availability of worldwide uranium resources in various categories—Reasonably Assured Resources, Estimated Additional Resources I and II, and the Speculative Resources—estimated by NEA and IAEA.[4] The projected uranium price is shown in Figure 2. The third module determines the uranium breakeven price. It signifies the price of yellowcake at which plutonium use in a given type of nuclear reactor—e.g. a light-water reactor or a faster reactor—begins to be economically competitive with a current type light-water reactor using uranium fuel and operating on the once-through mode.[5] The breakeven price is determined by comparing the cost of using plutonium bearing fuel in thermal and fast reactors and the cost of using uranium-dioxide (UO_2) fuel in thermal reactors. Our approach for this module is based on discounted cash flows and levelized lifetime costs. This methodology has been widely used worldwide.[6] The fourth module estimates the year at which the uranium price has reached such a level that the use of plutonium becomes economically competitive with contemporaneous thermal reactor using UO_2 fuel.[7]

Key Factors Driving the Plutonium Economics

Two cases will be developed for the model runs. Case A is based on reference values used in the NEA report.[8] Instead of using a fixed tails assay of 0.25% for enrichment, we however use an optimized tails assay, which depends on both uranium and enrichment prices and reflects better the tradeoff between uranium and enrichment requirements.[9] In Case B, we use values that are less favorable to plutonium use but may be more likely than Case A.

The economic competitiveness of plutonium use in thermal and fast reactors is driven by factors that are subject to large uncertainties. We first focus on thermal reactors. In addition to nuclear capacity growth and uranium resource availability discussed in the preceding section, one key factor is the fabrication cost of mixed-oxide (MOX) fuel versus that of UO_2 fuel. While the UO_2 fuel ranges from \$200 to \$350/kgHM with \$275 as the reference value,[10] the MOX fuel cost is much higher and is subject to larger uncertainties. Plutonium is highly toxic, much more radioactive than uranium, and weapon-usable. Using remote handling, dealing with smaller batch to avoid criticality and heavily safeguarding bomb materials are all more costly procedures. The reference value used by NEA is \$1,100/kgHM.[11]

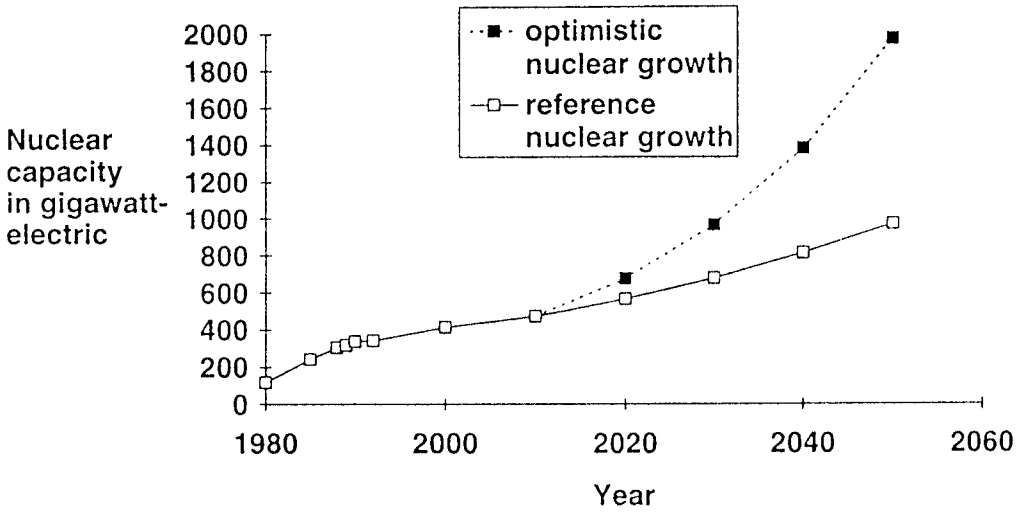

Figure 1. Projected nuclear capacity growth worldwide.

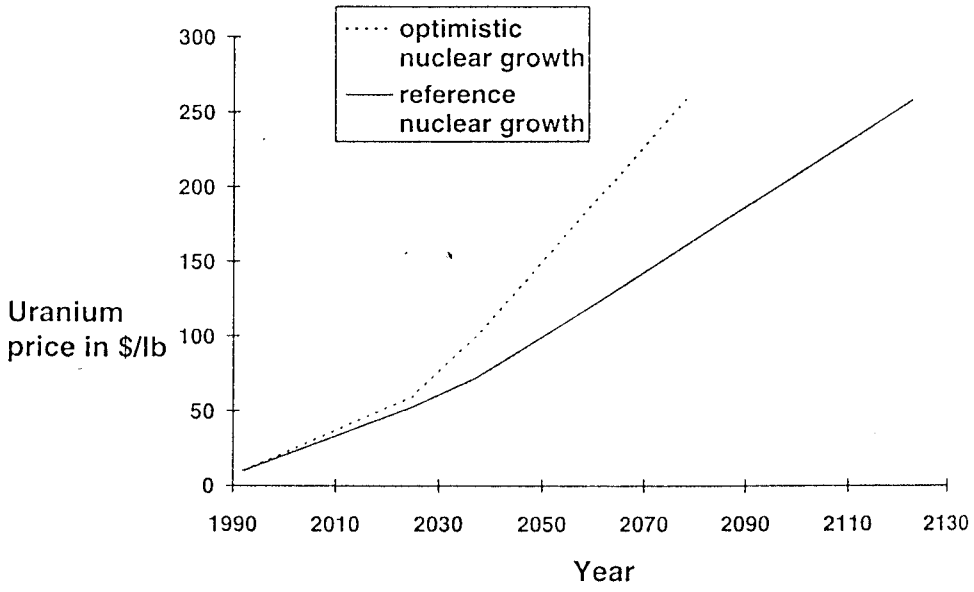

Figure 2. Projected uranium price in the absence of civilian plutonium use.

Some Western European estimates for MOX fabrication have ranged from $1,300 to 1,600/kgHM.[12] Other estimates run as high as $3,000/kgHM.[13] We will use $1,500/kgHM in Case B.

The real discount rate also affects the competitiveness of thermal recycle. NEA uses 5%, which reflects the cost of capital to the government. But, the private sector demands a much higher rate, say 10%. Using a lower rate for government projects makes the society suffer an opportunity loss, because the government is using money that can be put to better use in the private sector. We use 5% and 10% for both Cases A and B.

Another key factor is the reprocessing cost. The NEA uses a reference value of $720/kgHM with a sensitivity range from $540 to $720. An April 1991 study reported that the French La Hague and the British Sellafield have been charging their customers about $1,400 to $ 1,800/kgHM. But it also reported that a price of $900/kgHM has been offered for reprocessing in the post-2000 period. They manage to charge such a low price, because these facilities were financed by low-cost money from their governments and they managed to receive upfront money from their customers for the facilities' construction. Other countries will not be that fortunate. Recently, Japanese officials estimated that it may cost $20 billion to complete the 800-tonne-HM reprocessing plant at Rokkasho-mura during the next decade. Even at a 5% discount rate, the levelized capital cost alone would amount to $1,600/kgHM. But, a private venture would have a much higher discount rate or required rate of return. At a 10% discount rate, the capital cost would be $2,700/kgHM. Ray Sandberg of Bechtel Corp. estimated that the private sector cost of capital would lead to a reprocessing cost of the order of $2,000/kgHM.[14] In this case, the capital cost would have to be substantially less than $20 billion, especially when one also has to include the sizable annual operating and maintenance cost of a reprocessing plant. In this paper, we use $1,500/kgHM in Case B. It should be noted that NEA's reference estimate of $720/kgHM has included the disposal cost of low- and intermediate level waste and the vitrification and storage cost of high level waste. This makes the reference cost optimistic.

NEA assumes that the cost of vitrified high-level waste disposal to be $90/kgHM, while the cost of encapsulation and disposal of once-through spent fuel is $610/kgHM.[15] NEA based its $610/kgHM figure on Swedish and German data. The U.S. data, however, yield a substantially lower value of $140/kgHM, which is partially explained by the economies of scale resulting from the much larger amount of U.S. spent fuel. We will use the U.S. value in Case B. There could also be a bias for NEA to use, in the reprocessing option, 56 years as the time from spent fuel discharge to the disposal of the vitrified high-level waste, but a shorter 40 years for the direct disposal of spent fuel in the no-reprocessing option. In Case B, we use the same 56 years for both options. Since even at the lower discount rate of 5% the discounted disposal costs are small in the first place, the adjustments we made here for the cost and time of disposal affect the result little.

There is also a tendency to expect the costs of plutonium activities to decline over time, yet to keep the technologies and costs of current thermal reactors operating on a once-through mode unchanged. This view will lead to an overestimation of the attractiveness of plutonium. For example, NEA uses $110 per separative work unit (SWU) as the reference value with a range from $80 to $130. Yet, as pointed out by NEA itself that "the introduction of new technologies, such as advanced centrifuge and laser enrichment, is expected to provide additional enrichment capacity at prices substantially below those from existing plants due to lower energy requirement." It further says that "it is possible that enrichment prices could decrease by 2 per cent per annum in real terms."[16] We use $70/SWU in Case B.

As to plutonium use in fast reactors, all the factors discussed above are key drivers. In addition, while the existing thermal reactors can be modified at low cost to use MOX fuel, the plant capital cost for a fast reactor can be considerably higher than a thermal plant. One reason for the higher cost is the use of sodium, instead of water, as reactor coolant. Sodium is highly chemical-active and opaque, and forms radioactive isotopes under irradiation. These characteristics make equipment for safety and for operating and maintenance, including fueling and refueling, more complicate and costly. The plant capital cost of a matured fast reactor has been estimated to be 10% to 100% higher than that of a contemporaneous light-water reactor (LWR). The aforementioned NEA report does not analyze the economics of fast reactors. We will assume that the capital cost of a fast reactor is 20% higher than that of a LWR in this paper.

Breakeven Price/Year and Recommendations

Table I shows the key parameters for calculating the uranium breakeven prices and years for Cases A and B. Using NEA's input parameters in our model, we found the uranium breakeven price to be $\$44/lbU_3O_8$ (Case A with 5% discount rate). If one also uses the uranium price projection of NEA, the plutonium use in pressurized-water reactor (PWR) will not be economical until around 2050.[17] Thus, using NEA's own assumptions, one would find that thermal recycle will not be competitive with PWR operating in the once-through mode for 65 years. Then, thermal reprocessing can be postponed. Our projected uranium price shown in Figure 2 rises faster than that of NEA in order not to underestimate plutonium's benefits. Our breakeven year is around 2015 (Table II). Considering also other cases in Table II, we found that thermal recycle will be economical sometime between 2010 and 2080.

Plutonium proponents might select the most favorable case in which thermal recycle will be economical in about fifteen years. In that case, one could argue that countries should continue their current plutonium activities. The problem is the danger of subnational and national diversion of weapon-usable materials. This risk inevitably comes with the plutonium commerce. Moreover, even when thermal recycle becomes economical, the benefits will be small in relative terms. The cost

savings of plutonium use are only a fraction of the natural uranium cost, and the natural uranium cost itself in a LWR(OT) is only a small percentage of the total nuclear electricity generating cost.[18] Another benefit of plutonium use is to slow down the rate at which the uranium price will rise. Let us conduct a regret analysis by considering the scenario in which all of NEA's assumptions come true. Then, thermal recycle is competitive when the average uranium price during a reactor's lifetime is $\$44/lbU_3O_8$. If NEA's projection on future uranium price also holds, thermal recycle would not be economical until around 2050 and the energy planners would have little to worry about postponing thermal recycle. To make the case much more favorable to plutonium, let us further assume that thermal recycle will be economical by the year 2014 instead (Case A with 5% discount rate and optimistic nuclear growth). Moreover, because of immediate proliferation concern, the world is assumed to have adopted a policy of indefinite postponement of thermal recycle, and consequently thermal recycle will not be introduced until 2034 or twenty years later than 2014. Without thermal recycle, the uranium price rises to $\$92/lbU_3O_8$ by the year 2034 (according to the optimistic nuclear growth curve in Figure 2). Had thermal recycle been massively deployed by 2014, the annual uranium consumption could drop by a third. Consequently, we assume that the uranium price rises by a third less. Then, the uranium price could have risen to only $\$76/lbU_3O_8$ instead. Thus, electricity from a LWR(OT) using $\$92/lbU_3O_8$ would cost 1.5 mill/kWh more than that of a LWR(R) using $\$76/lbU_3O_8$. During the period from 2014-2034, the average electricity cost of the LWR(OT) would be higher by about half of the 1.5 mill/kWh or 0.75 mill/kWh, which translates into about 2% higher electricity costs as a result of untimely delay in massively deploying thermal recycle. This 2% can, however, be considered as insignificant. The absolute value would be about $5 million per year for each 1,000 MWe LWR(OT) plant. It would be difficult for one to construct a credible scenario in which the use of plutonium in thermal recycle would save as much as 10% of the total nuclear electric cost. In relative terms, even a 10% increase is tolerable, as there are other causes that would cause the electric cost to rise by 10%. In absolute terms, it would amount to substantial amount of money in that case. The final decision on thermal recycle will hinge on the tradeoffs of potential economic benefits and proliferation risks. We do not think that even a 10% savings in electric cost is worth the risks, especially when we consider how unlikely that the l0% savings will be realized and how likely that the risks will be.

Table I: Key Parameters for Calculating Electricity Generating Costs (1991 U.S. dollars).

	LWR(OT)	LWR(R)	LMFR
Plant capital cost, $/kWe	2,300	2,300	2,760
Plant capacity factor	0.75	0.75	0.75
Enrichment, $/SWU	110-70	110-70	—
UO_2 fabrication cost, $/kgHM	275	275	—
MOX or fast reactor fuel fabrication cost, $/kgHM	—	1,100-1,500	1,300-1,800
Reprocessing cost, $/kgHM	—	720-1,500	1,440-1,800
Spent fuel transport & storage, $/kgHM	230	50[a]	50[a]
Disposal Cost, $/kgHM	610-140	90	90
Annual requirement, kg of reactor-grade Pu(t)/GWe-yr	—	400	1,840
Annual charge, MTHM/GWe	18.7	18.7	19.4
Plant life, year	30	30	30

Note: LWR(OT) = light water reactor (once through), LWR(R) = LWR(reprocessing) with MOX fuel in 1/3 core, LMFR = liquid metal fast reactor, SWU = separative work unit, Pu(t) = total weight of all plutonium isotopes, HM = heavy metal, i.e., uranium and plutonium, MTHM = metric ton of HM, Gwe = gigawatt-electric. When two numbers are shown, they are used for Cases A and B respectively. [a] Transport cost without storage.

Table II: Uranium Breakeven Price in $/lb$U_3O_8$ and Year.

Case	Discount Rate	Nuclear Growth	Breakeven Price		Breakeven Year	
			LWR(R)	LMFR	LWR(R)	LMFR
A	5%	Optimistic	44	152	2014	2050
A	5%	Reference	44	152	2017	2075
A	10%	Optimistic	34	181	2008	2058
A	10%	Reference	34	181	2011	2087
B	5%	Optimistic	160	225	2052	2069
B	5%	Reference	160	225	2077	2106
B	10%	Optimistic	112	243	2040	2075
B	10%	Reference	112	243	2055	2117

Note: Case A uses the reference parameters in *The Economics of The Nuclear Fuel Cycle* by the Nuclear Energy Agency, OECD for calculating the electricity generating costs for LWR(OT) and LWR(R). Case B uses parameters that are less favorable to plutonium use but still probable. Numbers are not rounded for the convenience of interpolation. LWR(OT) = light water reactor (once through), LWR(R) = LWR(reprocessing) with MOX fuel in 1/3 core, LMFR = liquid metal fast reactor.

Energy security has often been raised as a key factor in pursuing plutonium. But, thermal recycle reduces only about 30% of the uranium requirement, and there are other ways to save even more uranium without resorting to the use of separated plutonium.[19] It is not prudent to plunge into thermal recycle, because the world will incur substantial proliferation risk but little and uncertain economic benefits. In term of energy security, it is much more justifiable to develop the liquidmetal fast reactor. Unfortunately, the proliferation risks are also present in plutonium-fueled fast reactors. At the same time, these fast reactors will not become economical until sometime between 2050 and 2120 (Table II). Therefore, there is no urgency to commercialize fast reactors, and the world should delay the decision of their commercialization by two decades. In the meantime, the world should be searching for proliferation-resistant alternatives to plutonium. There are many promising options that are worthy of pursuit. They include:

- Prolonging the world's reliance on existing reactors in the once-through mode. This entails improving the reactors' efficiency and identifying additional uranium resources at current and higher prices.

- Encouraging development of advanced nuclear reactors that are more efficient than current once-through reactors and more proliferation-resistant than plutonium-based reactors. Both uranium- and thorium-based fuel cycles should be considered.

- Confining sensitive civilian nuclear materials and facilities within the five currently declared nuclear weapon states. During the interim, exceptions may have to be made for some Japanese and others' facilities that are already in operation. Nuclear Weapon States that continue their sensitive civilian activities should agree to share the benefits, if ever any, of plutonium use with other countries. As an added inducement, states without sensitive activities will be favored over states with such activities as sites for international fuel banks and non-sensitive, yet important, components of the international nuclear fuel cycle activities.

References

1. Separated plutonium is much more dangerous than plutonium still embedded in spent fuel, because separated plutonium no longer has the protection of the intensive radiation.
2. The model is described in Brian G. Chow and Kenneth A. Solomon, *Limiting the Spread of Weapon-Usable Fissile Materials*, RAND, Santa Monica, California U.S.A, MR-346-USDP, 1993, pp-21-60.
3. Nuclear Energy Agency, OECD, *Nuclear Energy Data*, 1992.
4. Nuclear Energy Agency and International Atomic Energy Agency, *Uranium: 1991 Resources, Production and Demand*, Paris, France, 1992.
5. A pressurized-water reactor is used here.

6. For example, see Nuclear Energy Agency, OECD, *The Economics of the Nuclear Fuel Cycle, 1994.* (Hereafter cited as *Economics of Nuclear Fuel)*
7. 0ur model assumes that, as soon as a plant begins operation, the whole lifetime uranium requirement will be secured through a long-term contract and that the requirement will be subtracted from the uranium resources immediately. In this way, if a reactor starts operation at the breakeven year, one can assume that it can obtain the uranium at the breakeven price for operations during its lifetime.
8. *Economics of Nuclear Fuel.*
9. At NEA's reference uranium price of $\$27/lbU_30_8$ ($70.1/kgU) and enrichment price of $110/SWU, the optimized assay is 0.259% and very similar to the value of 0.25% used by NEA. At $\$200/lbU_30_8$ and $110/SWU, the optimized tails assay is 0.088%, which is very different from 0.25%.
10. *Economics of Nuclear Fuel, p.* 50. In our paper, we follow the cited report by using 1991 U.S. dollar or ECU(European Currency Unil) with a conversion rate of 1 U.S. dollar=1 ECU. We will also quote numbers in other reports that are not in 1991 dollars. But, since these numbers are recent and their uncertainties are large, we do not find the need to convert these numbers to 1991 dollars. The unit for fabrication or reprocessing cost is dollar per kilogram of heavy metal, which includes plutonium and uranium. Some reports, including *Economics of Nuclear Fuel,* use dollar per kilogram of uranium. Since the weight of plutonium is generally much lower than that of uranium, the difference in two units is not significant and no adjustment has been made in this paper.
11. *Economics of Nuclear Fuel, p. 154.*
l2. Frans Berkhout and William Walker, *Thorp and the Economics of Reprocessing,* Science Policy Research Unit, University of Sussex, Brighton, East Sussex, United Kingdom, November 1990, p.22.
13. Paul Leventhal and Steven Dolley cited an estimated MOX fabrication cost of $3,100/ kgHM at the Hanau plant in Germany. *(A Japanese Strategic Uranium Reserve: A Safe and Economic Alternative to Plutonium,* Nuclear Control Institute, January 14, 1994, p.25).
14. Edward Giltenan, *Science Friction: Houv Technology, Time and Conciliation Could End the Bitter War Over Nuclear Waste,* NUKEM Market Report, November 1994, p.l8.
15. In this paper, we define spent fuel as discharges from nuclear reactors before reprocessing to recover plutonium and uranium. Waste is defined as the aqueous streams containing dissolved spent fuel after plutonium and often uranium have been recovered.
16. *Economics of Nuclear Fuel, p. 37.*
17. NEA assumes that the uranium price to be $\$19.2/lbU_30_8$ in the year 1990 and to rise 1.2% per year *(Economics of Nuclear Fuel, p.* 50). Thus, the uranium price according to NEA will reach $\$44/lbU_30_8$ in 2059. NEA uses a levelized price method to calculate the average uranium price over the lifetime of the reactor. This corresponds to a reactor introduction of about 11 years earlier or 2048. In other words, if a reactor starts operation in 2048, the average price over the 30-year lifetime will be $\$44/lbU_30_8$.

18. The use of plutonium saves enrichment as well. But, since enrichment price is not expected to rise, the purpose of plutonium use is to guard against the rise of natural uranium price. At NEA's reference uranium price of $\$27/lbU_30_8$ ($70.1/kgU), the uranium cost in a LWR(OT) is only about 5% of the total electricity generating cost.
19. For example, an once-through thorium reactor, if successfully developed, will use only half or even a third of the natural uranium required for an once-through light-water reactor.

The Rationale and Economics of Reprocessing

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Abstract

Three broad justifications for reprocessing are discussed: that plutonium is a strategic fuel resource; that direct disposal is not technologically mature and is no cheaper than reprocessing; and that reprocessing provides environmental benefits in radioactive waste management. The paper argues that none of these proposed justifications have much force today in most national contexts. In the absence of a clear economic, strategic or environmental rationale, reprocessing seems likely to be restricted to a niche role in a small number of core reprocessor countries. The slow pace of the transition to interim storage-direct disposal regimes is due to the contractual, industrial and institutional rigidities inherent in the civil nuclear fuel cycle.

Introduction

Despite being a large and relatively mature industry, nuclear fuel reprocessing continues to generate controversy. Fifty years after the first industrial-scale reprocessing line came into operation and over thirty years after civil reprocessing began, the arguments over the costs and benefits of reprocessing are as fierce as ever. There are two main reasons for this. The first is that as an economic activity a number of serious social and political costs are associated with reprocessing. Perhaps the most sensitive of these is that nuclear weapons materials are made accessible, but environmental, health and safety concerns have also been significant. The second is that, unlike many other industrial activities which may be more hazardous or polluting, the reprocessing industry has not been able to establish a proper market basis for its activities. If a natural market existed for reprocessing, in competition with extended interim storage and direct disposal for instance, its legitimacy would be more secure.

The aim of this paper is to critically review three basic rationales which have been provided for reprocessing: recovered plutonium is a strategic resource; reprocessing is the most mature and economic fuel management option; and reprocessing has environmental benefits. Proliferation and security aspects will not be further considered here.

The paper argues that today these rationales no longer hold force in most national contexts today. The risks of giving up or deferring a decision to reprocess spent fuel are small when compared with the short-term benefits for utilities and

governments of interim storage. Confidence now exists in the technical feasibility of direct fuel disposal, and despite some difficulties, extended fuel storage is more politically acceptable than reprocessing. The result is that far from being the dominant spent fuel management route, reprocessing is now restricted to a niche role. Even so, more plutonium is being separated than is being recycled, and to avoid the continued growth of surpluses, reprocessing would need to be further constrained.

Rationales for Reprocessing

Advocates of reprocessing are in the habit of making promises about the future. This is normal for an industry with long investment cycles. From planning to execution, the commissioning of the new Thermal Oxide Reprocessing Plant (THORP) at Sellafield took 20 years. If the plant operates over its design life of 25 years, it will be shut down about 50 years after it was first conceived. Over that period nations will have foundered, an industrial revolution will have occurred, and the energy, environmental and security policies of most countries will have been completely recast. In making arguments for their industry, the advocates need to be able to show that reprocessing will bring benefits in the future. The problem is that the future changes with the present. Problems which appeared threatening during one period disappeared or were resolved by the next. Rationales for reprocessing have needed to adapt themselves to this reality.

Justifications for reprocessing fall roughly into three time periods. During an early period stretching until the mid-1970s, reprocessing was seen as the only viable spent fuel management option. Plutonium recycling in fast reactors was regarded as essential to the future of nuclear power, and this would provide energy security in an age of energy scarcity. In a second period, beginning in the mid-1970s and lasting until the late-1980s, the economic and strategic benefits of reprocessing came to be questioned and proliferation risks were first identified. The strategic justification now became less prominent and was replaced by a claim that reprocessing provided improved radioactive waste management. As the alternative interim storage/direct disposal route gained technical maturity and credibility it came to be seen as the benchmark against which reprocessing would be judged. In the current period justifications for reprocessing are almost entirely couched in relation to storage-direct disposal. New environmental and security claims have been made as the industry has sought to reinvent itself.

Plutonium As a Strategic Energy Resource

Rapid economic growth in the industrialised world during the 1950s and 1960s led to an equally rapid growth in energy demand. Up to the early 1970s a doubling of electricity demand every ten years could be assumed. Under these conditions rapid penetration of nuclear power into electricity supply systems was anticipated. The first oil shock of 1973 appeared to confirm a bright future for nuclear power. In 1975 the OECD forecast that world nuclear capacity in 1995 would

lie between 1300 and 1600 GWe and warned that at this rate of growth low-priced uranium resources would quickly be depleted.[1] Fears of uranium scarcity and fears of resource depletion more generally were reflected in high uranium prices in the late-1970s.

Projections of nuclear capacity growth and the scale of uranium resources concluded that thermal reactor programmes could be supplied from assured and reasonably assured uranium resources only until the 1990s. It was argued that nuclear power would need to be based on plutonium-fueled fast reactors beyond the turn of the century. The logic of this scenario was inescapable. Ever increasing energy demand would lead to fuel resource depletion unless more efficient use could be made of existing resources. For nuclear energy this meant that the great potential energy worth of uranium-238 transformed to fissile plutonium needed to be tapped. In this way the separation of plutonium in reprocessing became a key requirement of a secure energy policy in countries with nuclear programmes. Many governments devised national energy policies which placed great emphasis on the early commercialisation of fast reactors, and decisions were made to build new reprocessing capacity in Britain, France and Germany.

Reality Confounds Logic: The Demand Side

The story of the unraveling of this logic is very familiar. All of the main elements proved to be mistaken: economic growth slowed; electricity demand was de coupled from economic growth and grew even more slowly; the demand for new electricity generation capacity fell and the scale of the world nuclear parc began to stabilise at around 400 GWe.

These new conditions tended to undermine the strategic rationale for reprocessing and plutonium separation. Fears of uranium depletion were replaced by problems associated with overproduction and glut in uranium markets. During the 1980s uranium prices fell, production capacity was cut, utilities continued the draw down of their strategic stockpiles and there was a widespread retrenchment in the uranium supply industry. More recently the market has again been destabilised by the dissolution of the former Soviet Union and its trading block and the integration of the centrally-planned and free market economic systems. A global free market for uranium has emerged with a diversified supply base and large assured resources. Supply security has been further enhanced by the likely introduction of uranium from surplus military inventories. Uranium supply conditions will be shaped for about another decade by the draw down of civilian and military surpluses.

What about the longer term future? Secure and reliable energy supply is a fundamental requirement of a modern industrial society. Therefore a great deal of effort has been expended in planning against future uncertainty in world energy markets. Over the past decade or so, the problem of energy security has received progressively less attention. This is partly because the 1980s and 1990s have been a

period of energy surplus and low prices, but also because the nature of world energy markets has changed. No country today provides for all of its own energy requirements, and few now make this as objective of national policy. Russia comes closest. But, this leads to another conclusion—there is no correlation between economic performance and energy independence. Indeed it has been argued that energy self-sufficiency is bad for an economy, partly because it removes some of the incentive to export high value-added manufactures and services. Japan is a perfect example of a highly successful economy with few energy resources. Diversified and integrated energy markets are a central feature of the global economy today. The potential for major and damaging disruptions in supplies of energy resources has consequently greatly diminished.

Nevertheless, doubts may persist, and there may still be a desire to provide for extreme contingencies. There is no absolute way of achieving this. The best approach is to encourage diversity in energy supply, in the hope that the failure of one option will not jeopardise the others. Nuclear power has long been seen as an important means of providing such diversity, although even this claim is now open to question.[2] The question is whether energy security could most efficiently be enhanced through the introduction of plutonium-fueled reactors. In almost all contexts the answer is that it could not. Existing and foreseeable nuclear programmes could be sustained on known, conventional low-cost uranium resources.[3]

Reality Confounds Logic: The Supply Side

But the demand picture for uranium was not the only thing which had changed. Expectations on the supply side were also not fulfilled. During the 1980s fast reactor programmes failed, while the costs of reprocessing increased dramatically as tighter regulations were imposed.

Huge amounts of public and private money were spent on fast reactor development in Europe, Japan, the former Soviet Union and the United States, only four fast reactors are today operating and the prospects for commercialisation are gloomier now than ever. It is very hard to say when, if ever, the conditions will be right for fast reactors to start making a significant contribution to electricity production, even in Japan which has retained the strongest commitment to the idea of plutonium as a strategic fuel resource. With current technology, fast reactors cannot be competitive with conventional or advanced LWRs. If the fast reactor cannot compete with the LWR, it has no future.

Cost increases also affected utility commitment to reprocessing. Between 1970 and 1980 reprocessing prices rose by a factor of ten in real terms.[4] As a result, fuel and waste management rose steadily as a proportion of total fuel cycle costs, so that by 1986 they accounted for about 60 percent of total fuel costs in Germany.[5] By then, reprocessing accounted for about 40 percent of total fuel cycle costs and this figure has remained stable with the continued fall in uranium and enrichment prices. In

the more competitive electricity markets of the 1990s, when utilities are seeking to cut costs, large avoidable costs such as reprocessing are the first to be reconsidered.

To summarise. During the 1970s strong arguments were made for the strategic value of reprocessing, principally on the grounds that it would make available plutonium as a fuel resource which could thus enhance energy security. None of the assumptions about the demand for nuclear fuel have turned out to be correct, and the technological response to the threat of uranium scarcity has turned out to be flawed and costly. The strategic rationale for reprocessing has therefore been abandoned by most advocates.

Reprocessing As a Mature and Economical Fuel Management Option

By the time the collapse of the strategic case for reprocessing had been generally recognised in the early 1980s, substantial investments had already been made in fast reactors and reprocessing. Fast reactors could be closed down (Dounreay PFR)or their mission redefined (SuperphÈnix), but there were strong economic, legal and logistical incentives to maintain reprocessing. The reprocessing companies wanted to guard an industry which was still profitable, while their utility clients still had a need to ship irradiated fuel out of reactor storage ponds to reprocessing plants. In Germany, and for a period in the 1980s in Japan, reprocessing was mandated in nuclear licenses. Concurrently a concerted research and development effort had been underway since the mid-1970s in the United States, Canada and Sweden into an alternative fuel management route—interim storage and direct disposal of spent fuel. By the early 1980s reprocessing increasingly had to be justified in relation to storage-direct disposal.

A new rationale was developed based on three claims:

- reprocessing is the most technically mature fuel management route
- recycling plutonium in thermal reactors is economic and conserves resources
- reprocessing provides long-term environmental benefits

These arguments were aimed mainly at utilities, since in the absence of a strategic rationale, government policy became less concerned with reprocessing policy. We take the first two rationales together first.

Relative Technological Maturity

The claim that reprocessing/recycling was more technologically mature than storage/direct disposal was always rather weak. Pond storage of nuclear fuel is a standard part of all nuclear fuel cycles (whether civil or military) and can be regarded as a mature technology. For most fuel types extended fuel storage has also been proven. In addition, a series of new technologies emerged during the 1980s (vaults and casks) which were better suited for providing safe long-term storage. By

the late 1980s these technologies were receiving licenses in the United States and Europe. The rather false comparison made by reprocessing advocates was between reprocessing and the direct disposal of spent fuel. Accumulated industrial experience at reprocessing facilities was compared with the conceptual status of plans for the disposal of spent fuel in repositories.

A truer comparison would be between the status of fuel storage and reprocessing, and between research on the disposal of high-level waste from reprocessing and direct disposal. Given that the first systematic safety assessment of a high active waste repository was the Swedish KBS-3 study which considered the disposal of spent fuel, and given that this research has continued in Germany and North America, it is fair to argue that spent fuel has been at least as well studied as a waste form as vitrified high-level waste.[6]

Economics of Reprocessing

The second claim about the relative economics of reprocessing-waste disposal and interim storage-direct disposal has been the focus of much debate over the past ten years. Many approaches have been used and to a certain extent the approach taken will determine the outcome of the assessment. Most prominent recently have been the full-scale systems studies of the OECD Nuclear Energy Agency (1994) and the Energiewirtschaftlichen Institut (EWI) (1995). Neither of these studies is definitive because there are always uncertainties and national specificities, but they represent the current possible spectrum of views.

These studies model the total fuel cycle costs of a reprocessing-recycling system based in thermal recycle and compare this to the total costs of an open fuel cycle with direct disposal. The range of results produced by these studies is very wide, but all are agreed that under current economic conditions the reprocessing-recycle option is the more costly. The debate is over the width of the gap. Table 1 provides a breakdown of the results of two recent studies: the 1994 OECD study as interpreted by Cogema in a recent presentation; and a 1993 study by the Vereinigung Deutscher Elektrizitätswerke (VDEW). The OECD figures appear to show only a marginal difference between the relative costs of the two options, whereas the VDEW study shows that for German conditions the reprocessing-recycle option is over twice as expensive as storage/direct disposal. The main differences are the assumed cost of reprocessing and waste management, and the treatment of credits/penalties for recycling recovered uranium and plutonium. The EWI study showed a cost difference between the two options of about 25 percent.

More limited assessments have used the 'free plutonium' concept in which the cost of separating the plutonium in reprocessing is discounted.[7] This picture is closer to the reality faced by utilities today, since many regard reprocessing as a sunk cost to which they are committed through binding contracts with reprocessors. It also explains why penalties are attributed to plutonium recycling in the VDEW

Table 1: Cost comparison between reprocessing-recycle and storage-direct disposal options: back-end costs only (undiscounted costs, French c/kWh).[10]

	OECD/Cogema (1994)		VDEW (1993)[1]	
	Closed	**Open**	**Closed**	**Open**
Fuel transport	0.10	0.10	0.19	0.06
Fuel storage	—	0.31	—	0.58
Reprocessing	1.20	—	2.08	—
Spent fuel packaging	—	0.5	—	0.93[2]
Waste storage and packaging	—	—	1.16	0.23
Waste disposal	0.11	0.19	1.16	1.16
Subtotal	*1.41*	*1.10*	*4.59*	*2.96*
Uranium credit[3]	-0.18	—	+0.23	—
Plutonium credit[3]	-0.07	—	+1.81	—
Subtotal	*-0.25*	—	*+1.04*	—
Total	**1.16**	**1.10**	**5.63**	**2.96**

[1] Assumes a reactor efficiency of 0.33, a fuel irradiation of 45 GWd/t and an exchange rate of FF3.7:DM1.
[2] Assumes fuel conditioning plant throughput of 450 tHM per year.
[3] A negative entry implies a cost saving and hence a positive value attributed to recovered products.

study. Under the 'free plutonium' scenario the economics of MOX is a question of balancing the savings made in avoided fresh uranium ore purchases and avoided uranium enrichment with the additional costs of plutonium fuel fabrication. Production of MOX is more expensive than production of LEU fuel because of the added safety and security precautions needed in handling plutonium.

Assuming current and expected prices for uranium, enrichment and fuel fabrication, MOX fuel will be more expensive than LEU fuel. Even assuming the full-scale operation of large new MOX fabrication plants (Hanau, Melox), MOX fuel would cost about twice as much as LEU fuel. If reprocessing costs are all attributed to the cost of MOX fuel (uranium credits are discounted), then MOX fuel would appear to be as much as six times as expensive as LEU fuel.[8] This result matches the estimate of the break-even point for reprocessing vs. interim storage-direct disposal made by Hensing and Schulz.[9] In these conditions, rather than being an asset, plutonium must be seen as a liability. Even if uranium resources are conserved, it is unlikely that an economic case could be made for the large premium that would be paid with thermal plutonium recycling. All minerals are potentially valuable, but man exploits only those which are economic to exploit.

The Environmental Benefits of Reprocessing

Environmental justifications began being made for reprocessing during the 1970s when radioactive waste management first became a major political issue. Two principal claims have been made:

- that lower volumes of waste would be produced in reprocessing, and
- the toxicity of reprocessing waste streams was lower than that of spent fuel.

In the late-1970s, and again today, it was further argued that reprocessing opened up the option of destroying completely long-lived radionuclides through their partitioning and transmutation, so resolving one the most sensitive elements of controversies over nuclear waste management.

Lower waste volumes. European reprocessing companies have invested heavily in reducing the volume of low and intermediate wastes associated with reprocessing, leading to a three-fold reduction over the past 15 years.[11] However, even today the total volume of conditioned reprocessing waste is about 20 m^3/tHM, while the volume of spent fuel in a German Pollux cask is about 2 m^3/tHM.[12] Cogema has announced further volume reductions in the future and has even argued that reprocessing conditioned medium-active waste volumes will be lower than conditioned spent fuel waste volumes. However laudable these efforts, they still ignore the enduring problem of low active wastes which account for perhaps half of total reprocessing waste management and disposal costs.

But what advantages do smaller volumes bring? They clearly reduce storage and transport costs, but the benefits in terms of repository safety are less clear. The design and performance of a repository is primarily dependent on the heat output of the waste placed inside it. Although glassified HLW, since it does not contain plutonium, has a slightly reduced heat rate, this is not significant to repository design. Moreover, the decay heat associated with actinides in spent MOX fuel is an order of magnitude higher than for spent uranium fuel.[13]

Lower toxicity. The potential radiotoxicity index is also much used by reprocessors. They argue that higher long-term safety risks are associated with the disposal of spent fuel because plutonium is not removed from the waste stream. However, long-term safety assessments for a variety of repository designs and geological environments show that spent fuel can, in principle, be disposed of as safely as vitrified high-active reprocessing waste. The German repository concept assumes, for instance, that spent fuel and vitrified HAW will be disposed of in the same repository. Spent fuel is at least as good a matrix for fission and actinide products as glass, and new research into ceramic waste forms suggests that it may be better.[14]

Gross indicators of toxicity are not helpful in predicting the likely long-term safety of repositories. Site-specific safety assessments of the behaviour of radionuclides in real repository environments are needed. Such assessments are now achieving maturity and they show that long-term safety depends on the mobilisation of nuclides. Studies of plutonium mobilisation suggest that it will not move far out of the near-field of the repository under most conditions.[15] Removing plutonium does not therefore bring great improvements to long-term safety which is more closely determined by the prevalence of nuclides like neptunium-237, technetium-99 and iodine-129. These occur with the same concentration in spent fuel and reprocessing waste.

Partitioning and Transmutation (P-T)

More recently there has been renewed interest in France, Japan and the United States in the possibility of partitioning other long-lived radioactive materials (apart from plutonium) in a process very similar to reprocessing. These materials would then be irradiated either in reactors or in accelerator-based convertors. This would break them down into shorter-lived species which could be stored and eventually disposed of as short-lived low-level wastes. While worth investigating, the prospects of this extremely demanding and energy-intensive suite of technologies ever being viable appear to be very slim. Even if the technologies could be proven, they are likely to lead to new short-term risks which would outweigh any long-term risk reductions. Moreover, P-T will not eliminate the need for radioactive waste disposal. There will always be some fraction of nuclides present in the high level waste remaining after partitioning and transmutation.[16] The other risk of P-T programmes is that they will undermine the credibility of existing waste repository programmes by suggesting that these will not provide acceptable long-term safety.

The Prospects for Reprocessing

Over the next twenty years the prospects of reprocessing depend more on the availability of spent fuel storage capacity than on any clear economic, environmental or strategic advantage which reprocessing offers. In most countries reprocessing has become the default fuel management option because uncertainty persists in some places about the political acceptability of extended fuel storage. This is paradoxical since a dispassionate assessment would now conclude that fuel storage presents fewer risks than with almost any other activity along the nuclear fuel cycle. It is also clear that reprocessing does not remove the need for high active waste storage and disposal, it only displaces it.

No utility today is committed to reprocessing all its fuel, and an increasing proportion of fuel discharged seems set to be placed into interim storage. Reprocessing in the 1990s is the result of government and utility policies made in the 1970s when expansive plans for plutonium-fueled breeder reactors still had an appeal and when the alternative of long-term storage and disposal had not been

properly considered. Today the role of government policy is diminished and the main aim of utilities is to operate reactors economically and securely. The pressures which remain on utilities to reprocess are either insecurity about spent fuel storage (as in the case of U.S. utilities considering reprocessing), or a deep-seated institutional commitment to reprocessing (as in France, Russia, the UK and Japan). In these 'core' countries reprocessing seems likely to remain the dominant fuel management option, while elsewhere interim storage and direct disposal will be preferred. The withdrawal of German utilities from post-2000 contracts with Cogema and BNFL and the reprocessing moratoria in Belgium, Switzerland and Spain are all symptoms of this dual pattern of fuel management regimes being established.

Looked at in the round, reprocessing today occupies a niche position as a fuel management strategy. A global survey of plutonium discharges from power reactors shows that less than one-fifth of all plutonium discharged to date have been reprocessed.[17] Despite the rapid growth of reprocessing capacity through the 1990s, this figure will not greatly change over the coming ten years. During this period a major problem for utilities with reprocessing contracts will be recycling of plutonium and the establishment of stores for reprocessing wastes. Large inventories of civil plutonium already exist (some 110 tonnes of total plutonium at the end of 1993) and these are likely to be added to by continued reprocessing. It is therefore quite incorrect to argue that the problem of plutonium inventories, whether civil or military, can be solved by continuing to reprocess. Reprocessing is the cause of this problem, not its solution.

In the longer-term, the prospects for reprocessing depend on the fuel cycle policies of the 'core' reprocessor countries. Electricitè de France (EdF) retains a strong commitment to reprocessing and can absorb the economic penalty this represents relative to a once-through cycle. Nevertheless, EdF has always had a pragmatic attitude to reprocessing, and it is now developing an independent centralised fuel storage facility. With greater room to manoeuvre it may begin to rethink the balance of its fuel management strategy.

Japanese reprocessing policy is outwardly still robustly committed to reprocessing, but Japanese utilities are now balking at the extremely high cost estimates for the Rokkasho-mura reprocessing plant. Recent reports put the cost of this facility at $2-4 trillion ($20-40 billion at current exchange rates). Recent liberalisation of the Japanese electricity supply industry has meant that utilities are under strong pressure to control costs. At these rates, the cost of reprocessing begins to make nuclear power uncompetitive with coal. The future of reprocessing in Japan is therefore more uncertain than ever before.

Reprocessing in the UK is tied to the future of nuclear power. The recent government policy paper on the nuclear industry showed clearly why no new investment in nuclear power can be expected in Britain for the foreseeable future. Fuel discharged from the Sizewell B PWR will not be reprocessed. Reprocessing in

the UK will therefore remain a service operation for a progressively shrinking number of gas-cooled reactors beyond the turn of the century. Whether the THORP plant can be economically viable processing only Advanced Gas-cooled Reactor fuel after 2004 remains to be seen. Lastly, the Russian reprocessing industry, while still receiving strong government support, is clearly in trouble. Future economic viability of both the Mayak and Krasnoyarsk operations will depend on the ability to attract foreign business. Although cheap, the political and environmental acceptability of Russian reprocessing remains in doubt.[18]

Conclusion

Large industries need large justifications. Over long cycles of investment industrial, financial and political support for projects needs to be nurtured and maintained. The reprocessing industry is no exception. Its existence and continued survival depend partly on the ability to project a compelling case for itself. The problem is that the economic, environmental and security conditions of the reprocessing industry have undergone revolutionary change over the past 30 years, while the capacity of the industry to respond has been limited. Long-term justifications have been replaced with present day justifications, few of which have stood up to scrutiny. The four basic planks of the case for reprocessing: strategic; economic; environmental and security, are today profoundly questionable.

It can be argued that even if the grand justifications have failed, the commercial reality is that an industrial demand exists (or has existed) for reprocessing. Utilities have signed contracts for their own reasons and that is enough evidence to justify the industry. But this argument appears to accept that reprocessing has become the default fuel management route in most countries, playing a diminishing role in the future.

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Plutonium Recycling, a Mature Civilian Industry and a Key Contribution to the Weapons-Plutonium Inventory Disposition Issue

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Abstract

The reprocessing/recycling industry has now attained in France a solid operating experience, showing excellent records in terms of productivity, quality of products, competitivity, protection of the workers, the population and the environment. In France, the La Hague reprocessing facility, the Cadarache and Marcoule (MELOX) MOX fabrication plants are experiencing satisfactory operations, with the MELOX plant smoothly coming on line. On the reactor side, plutonium recycling is growing both in France with the progressive introduction by EDF of MOX fuel in up to 28 PWRs, and in other European countries, then in Japan. Such satisfactory experience may be brought to help solving the current issue of weapons plutonium inventory disposition: "moxification" of this weapons-plutonium will product electricity while burning and deteriorating (in terms of weapon-value) plutonium.

Advantages of this management over alternate options will be described: short-term industrial availability, natural resources sound management and environment respect, economy value, contribution to anti-proliferation measures.

The Commercial Recycling Maturity

Seven PWRs are currently loaded with MOX fuel in France, and a total of 18 reactors in Europe. By the year 2000, a total of 40 to 50 European reactors will recycle plutonium in 30 % of their cores.

By the end of this year, some 20 tonnes of commercial plutonium will have been introduced in MOX fuel. By the year 2000, a total of some 60 tonnes of civilian plutonium will have been moxified, representing the electricity production of 60 million TOEs. Japan will soon start a smooth and decisive program.

The in-core experience reported by the utilities proves no operational difference between UO_2 fuel and MOX fuel in terms of performance and safety. This is not surprising as already in a pure UO_2 fuel, up to 40 % of the fission process producing electricity comes from the plutonium created in-situ.

Regarding the MOX fabrication experience in Europe, the industrial reference is growing up: together with the operating facilities in Belgium and France, the large

MELOX facility at Marcoule (France), which is currently coming online, will bring total fabrication capacity to some 160 tonnes of MOX fuel per year. This means that up to 8 tonnes of commercial plutonium will be incorporated in MOX each year. By the year 2000, the European civilian capacity will increase to 400 tons of MOX fuel per year, using about 25 tonnes of plutonium per year. (In terms of quantities this represents half the U.S. excess inventory). On its side, Russia is seriously considering the industrial implementation of MOX recycling in its VVERs.

Moxification of Weapons-Plutonium

Both the U.S.A and Russia are currently assessing various options for the dispositions of their excess inventory of weapons-plutonium.

Incorporation of such plutonium in MOX fuel for electricity generation is generally identified as a first choice, with further studies assessment and E.I.S under progress for a policy decision.

The commercial plutonium recycling industry can testify upon the soundness of this management policy with respect to the four following criteria: industrial availability, natural resources management and environmental consistency, economic soundness, contribution to anti-proliferation measures.

Industrial Short-Term Availability

Starting from the commercial plutonium MOX fabrication experience the transposition to weapons-plutonium characteristics does not bring major difficulty. For example weapons grade plutonium is easier to handle than the reactor-grade plutonium already in use: specific thermal power is 7 to 10 times less, radioactivity is also seriously reduced (alpha, gamma, and neutrons). However criticality considerations would lead to the need for some specific adaptations of the civilian MOX technology for example, smaller size equipment in the first part of the facility. This is not perceived as a difficulty. In fact the specific adaptation required would depend on the form under which weapons plutonium is released to the commercial cycle.

The primary alternative that has been identified for weapons plutonium disposition, vitrification, is indeed also a well developed technique when applied to fission products, particularly in Europe, as a key component of reprocessing. Hundreds of canisters have been safely produced. But the glass here has been designed to incorporate high-level waste and minute quantities of actinides.

Incorporation of significant percentages of plutonium in glass, even the “French” glass which is viewed favorably by many leading experts, would require further specific experimentation and development, while the technology of incorporation in MOX fuel is readily available.

Natural Resources Management and Environmental Consistency

The disposition of the 50 tonnes of excess inventory weapons-plutonium through moxification leads to an electricity production of some 350 billion kWh, or the equivalent of 50 million T.O.E. Vitrification and/or direct disposal of the same material would not produce any return, but would indeed consume some energy. What country can afford to deliberately turn this substantial available energy source, almost one third of all the North Sea oil fields yearly production, from a resource into a waste ?

But every debate on civilian, and now weapon plutonium is obscured by irrational attitudes and passionate claims regarding plutonium as a symbol, leading to extraordinary confusion in political and media arenas, cleverly staged by nuclear opponents.

Regarding the environmental aspect of weapons plutonium disposition, one should clearly distinguish between the short-term period and the long-term horizon:

- On the short to medium term, the fuel cycle back-end industry, dealing with spent fuel, high level waste and plutonium, has clearly demonstrated its capacity to handle these materials with a high degree of safety and environmental protection.

  For instance, in the La Hague reprocessing plant today, the individual dose to the average worker is 0.26 mSv per year (1994), that is 10 % of the natural exposure of each of us.

- On the long-term horizon, weapons-plutonium disposition through moxification is a straightforward way to consume half the original quantity of the excess inventory.

Vitrification, on the other hand, would simply retain all the material in the glass logs.

More generally, regarding plutonium toxicity, dreadful figures are being publicized to threaten a public unfamiliar with nuclear health physics. The scare tactics go something like this: as one single microgram of plutonium could supposedly induce a cancer (in very particular conditions), then 1 kg of plutonium could induce 1 billion cancers. Such “causation” figures deliberately ignore the practicalities of distribution of the material. If one considers that U.S. and Russian nuclear weapons atmospheric testing have dispersed since the G0’s **some 4000 kg** of plutonium in the atmosphere, the above “reasoning” would lead to 4000 billion fatalities.

But as absurd as they are, these figures and allegations seem to impress the **general public** to an extent that the irrational fears of "demon plutonium" that have been fostered over the years, are not that easy to correct at the political and media level.

Economic Soundness

When deciding for moxification of the weapons plutonium inventory licensing activities and industrial deployment can start almost immediately, while vitrification would first require some development time and costs. The 350 billion kWh electricity production from weapons plutonium MOX fuel will return a large economic benefit, maybe $ 12 to 15 billions in current money, against the cost of the program, while vitrification can only show absolute costs without any return.

Further cost assessments would be needed to reliably compare the economy of the options, but we can quote a cost evaluation presented by P. Goldschmidt, General Manager of the Belgian Company Synatom on recent occasions: "Warhead plutonium recycling in light water reactors is economically justified. The fastest, safest and most economical currently available way for disposing such plutonium is to use it as MOX fuel in existing light water reactors. . . The money saved in this recycling scenario, compared with the (vitrification and disposal) scenario, ranges between $ 10 and $ 20 per gram plutonium. For 100 tons warhead plutonium, this means savings of $ 1 to $ 2 billion."

This is consistent with the economic assessments of MOX fuel use in the civilian cycle. The French utility EDF has repeatedly confirmed the economic viability of commercial plutonium recycling in its PWRs. And the utility is demonstrating this by implementing a progressive, large MOX recycling program.

Contribution to Anti-Proliferation Measures

Here again, disposition of weapons plutonium through recycling in MOX fuel presents a distinct advantage over other alternative options (including vitrification) for 3 primary reasons:

- PuO_2 transformed into MOX fuel adds a technical barrier against would-be users of the material;
- Half the quantities of initial plutonium are destroyed (and more, if multiple recycling could be envisioned);
- The isotopic composition of the plutonium is degraded to a quality that would make it virtually unsuitable for weapons use.

On the other hand, vitrification and disposal of the weapons plutonium inventory appears as constitution of a "plutonium mine" available in the future in

quantity and quality for would-be proliferation, even if reextraction of such plutonium from the glass logs proves difficult and costly.

But in fact the debate regarding plutonium and proliferation is also obscured for political reasons, when one does not draw a distinction between:

- National proliferation programs, which historically have always been based on indigenous development of a complete production capability for nuclear weapons components: highly enriched uranium or weapons-grade plutonium.

  No country has ever tried misusing commercial materials: low enriched uranium or reactor-grade plutonium.

  Beyond the technicalities, such important, complex questions are obviously to be addressed at the political and diplomatic levels.

- Hypothetical terrorist attempts to divert some materials for clandestine assembly of a few nuclear "devices" which relates to physical protection concerns. Here the nuclear industry, and the Defense organizations (at least in our countries) have to maintain efficient systems.

Conclusion

With regard to the above four criteria, disposition of weapons plutonium through MOX recycling appears preferable to other alternatives, including vitrification.

This is at least a European, practical and industrial viewpoint, drawing on our operational experience.

Now what will be the actual solution to be preferred in the U.S.A and in Russia for disposition of their excess inventory ? That is obviously for the United States and for Russia to decide, for their own reasons.

Clearly the choice made by the U.S.A must be considered by the rest of the **responsible world** actors as a legitimate choice for the U.S.A; exactly as it is legitimate for **other responsible** countries to make their own choices in nuclear energy, fuel cycle and waste management policies.

U.S. Participation in an Advanced Nuclear Fuel Cycle: A Decision-Theoretic Analysis

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Abstract

We introduce a decision-model for U.S. government evaluation of the development of advanced nuclear fuel cycles involving plutonium recycle. We use a highly aggregated model of the world economy to estimate electricity demand in the next sixty years. We develop and critique a probabilistic model for the theft of fissile material from the commercial power sector by subnational groups. We then introduce a game-theoretic model of surreptitious diversion by a national actor. Finally, we briefly discuss valuation of the theft or diversion of fissile material.

Introduction

While the original concept of the nuclear fuel cycle included reprocessing of spent fuel, mainly for the purpose of extending the uranium resource, several events starting in the seventies combined to change this prospect.

First, new uranium ore discoveries, coupled with lower than anticipated world electricity demand, drove the cost (at least in the U.S.) of using fresh uranium fuel below that of using reprocessed fuel, a situation which is not expected to change for some decades. Second, political opposition to nuclear power and to plutonium in particular has raised the cost of nuclear power relative to other power sources in the U.S. and elsewhere. Third, the relative ease with which separated plutonium can be handled and transported as compared with plutonium left in spent fuel, together with the fact that reactor-grade plutonium can be used to make nuclear explosives, has led to concern about the linkage between reprocessing and possible diversion and theft of fissile materials. The U.S. government has opposed reprocessing for civilian nuclear power for this reason, and this year abandoned all research and development on such a cycle, even though the R&D was specifically aimed at reducing the physical availability of plutonium for diversion or theft.

What's Changed

Why reconsider this decision? There are two reasons, one based on economics, one on politics, both related more to events outside the U.S. than within the U.S.

The economic reason stems from anticipated world economic and therefore electricity demand growth, together with the size of low-cost uranium reserves. As discussed in more detail in connection with the economic model, even low estimates of population and economic growth over the next sixty years, together with liberal estimates of how much use will be made of conservation, solar and other renewables, and of how much carbon emissions will be tolerable, lead to an increase in world nuclear reactor power by at least a factor five. At this rate, present known and speculative uranium reserves available at costs that do not increase the price of electricity are not sufficient to fuel these reactors without reprocessing. There is therefore a significant chance that much of the world, and particularly such now-industrializing countries as China and India, will turn to reprocessing for economic reasons. It is noteworthy that much of the anticipated growth is slated to take place in East and South Asia, and perhaps in Russia also. The countries in these areas can be expected to place a high priority on economic growth, and therefore on reliable provision of electricity at reliable prices. They have not historically been amenable to U.S. pressures which they could interpret as opposing their continued growth.

The political reason stems from the fact that some major countries (Britain, France, Japan, Russia) have taken a different approach to the nuclear fuel cycle from that of the United States and others (China) plan to do so in the future, and are maintaining this approach despite the economic costs involved, albeit several projects have been slowed or abandoned.

Their stated motivation has been security of energy supply, and capability to export civilian nuclear technology over the long term. Some in the U.S. have ascribed their continued support of reprocessing to bureaucratic momentum. Given the economic projections noted above, however, the stated motivations of these countries are likely to be supported by events. As a result, the U.S. may, if it continues in its present stance, find itself in a position where it cannot influence politically or profit economically from nuclear power expansion world wide.

These developments of course are beset with uncertainty, and are slated to occur some half-century from now. How much should the U.S. invest now, in money and in possible increased present risk, to make money and alleviate risk half a century from now? This is the question to which our research is addressed. In this paper, we will present only preliminary results, based on preliminary and overly simple economic and security models. We will however point out the direction of our further research.

In what follows, we first describe the economic model, then the security model. Our conclusions are highly preliminary.

Modeling the Economic Growth of Plutonium

This section comprises a preliminary estimate of electricity demand assuming constant real prices. In subsequent work, we plan to incorporate a more realistic economic model which will allow for variations in economic growth, prices, and savings. The purpose of this simple model is twofold. First, it provides a point estimate of the future world nuclear energy market, which is useful for attempting to quantify the returns to R&D of any U.S. program. Second, it may be the case that theft of fissile material by subnational groups is related to its consumption and/or transportation rates. The more ubiquitous plutonium *is*, the more likely it may be stolen.

The demand for electricity is affected mainly by population, state of economic development and available conservation measures. The demand used was obtained under realistically optimistic assumptions for population growth, introduction of conservation technologies, economic growth, and international cooperation.[1] We assume a low population estimate of nine billions by 2060. Population could grow faster but probably not more slowly than this. We assume a world economic growth rate of 2.3%. Lower growth has often been seen in the past, but lower world growth than 2.3% would entail prolonged stagnation and poverty and carries a major potential for human suffering and political instabilities. Prices, of course, have an effect both on economic growth and on what conservation measures are implemented.

After 2010, most of the energy in the world will be used in what are now industrializing countries. The total rate at which energy is used in the industrialized countries today is roughly 7.5 kW per person, in the Less Industrialized Countries (LICs) perhaps 1 kW per person. If major strides are made in energy efficiency, and most of the LICs increase their respective standards-of-living markedly by 2060, a world population of nine billion may require 3 kW per person, or 27 TW total. This is slightly more than double the current world demand. A population of 14 billion with per capita consumption of 5 kW implies a world consumption of 70 TW, or five times the current demand.

Nuclear energy currently provides approximately 20% of the world's electricity, or 0.34 TWe. There are about 420 plants in 32 countries. Plants under construction will bring these numbers up to 0.4 TWe and 500 plants by the end of the decade. A continued 20% nuclear energy contribution to the world's electricity supply means that there would be about 600 plants in the world in 2060 under the scenario outlined above. If the nuclear energy contribution were to rise to 40% in order, for instance, to keep carbon dioxide emissions to no more than twice what they are now, as assumed here, there would be more than 4,000 such nuclear plants. Half or more of the plants would be in Asia, several hundred in China alone. The detailed calculation, with assumptions, is presented in Table 1.

Table 1. Estimate for the Number of Nuclear Plants in 2060.

Parameter	Low Scenario	High Scenario	
Per Capita Energy Usage in 2060	3	5	$kW_{thermal}$
Electricity Fraction of Energy Usage	0.33	0.4	
Per Capita Electrical Usage in 2060	0.99	2	$kW_{thermal}$
Efficiency of Electricity Generation	0.33	0.4	
Direct Per Capita Electricity Usage in 2060	0.3267	0.8	kWe
Fraction of Electricity Generated by Nuclear	0.2	0.4	
Per Capita from Nuclear in 2060	0.06534	0.32	kWe
World Population in 2060	9×10^9	14×10^9	people
Total Electricity Usage in 2060	5.88×10^8	4.48×10^9	kWe
	0.588	4.48	TWe
Number of 1000 MW Plants	588	4480	

To calculate the limits of the uranium resource, we assume an existing reserve at prices near competitive to coal at 6 million tonnes of yellowcake, corresponding to about 1 million tonnes LEU at 3% enrichment. With an average burnup of 40,000 megawatt-days/tonne, this yields a total supply of fuel for the open-cycle of 100 TWy (thermal) or 40 TWey.[2]

To calculate the consumption of uranium through 2060, we use the 1994 EIA[3] estimates of low and high nuclear power utilization through 2010, and then fit an exponential growth curve between 2010 and 2060. A graph of this estimate is presented in Figure 1.

Assuming a nominal plant capacity of 1000 MW (thermal), an estimate of world uranium consumption uranium through 2060, as well as the shortfall given the 40 TWey limit can be calculated. For 2000 plants, world consumption is 30 TWey. For 3000 plants, it is 42 TWey, including a shortfall of 2 TWey. For 4000 plants, it is 54 TWey, including a shortfall of 14 TWey. The shortfall, if price and demand are constant, must be made up from other sources. Given the optimistic estimates of the use of renewables, it is unlikely that they could be stretched further. The shortage then represents the amount to be filled by additional coal consumption or by closed-cycle nuclear. Of course, earlier introduction of the closed-cycle by some nations may occur, in which case plutonium consumption will replace some uranium earlier.

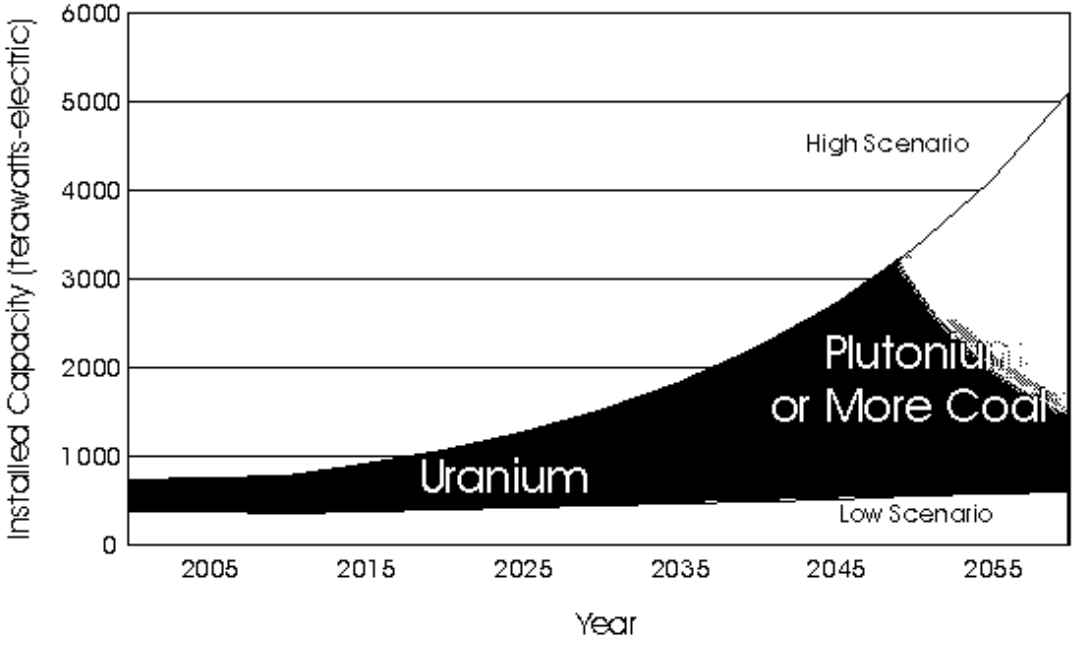

Figure 1. Consumption of plutonium will be a function of the uncertain growth in electricity demand. More coal could also be substituted for plutonium.

Lastly, note that 1 TWey represents 2500 plants of nominal 1000 MW (thermal) capacity operating for one year, so for an estimate of 3000 nuclear plants, we anticipate 5000 reactor-years of closed-cycle (i.e., plutonium-based) nuclear operations.

There are quite a few studies of uranium pricing and resource exhaustion. For example, Chow [1995] finds that MOX fueling will become competitive with the once-through cycle in LWRs between 2008 and 2077, depending on various assumptions. Rodwell [1995] finds that MOX will be competitive in 2057 at the earliest. Further work on the economics of plutonium will involve reconciling these other estimates with an uncertainty analysis.

How the growth of plutonium-based nuclear power affects security is the subject of the next section.

Modeling Theft

We distinguish between two security risks associated with a plutonium-based nuclear fuel cycle:

- theft of a small amount of fissile material by a subnational group, and

- diversion of fissile material by a state for the purpose of developing a nuclear weapons program.

This section focuses on the risk of *theft*. There is a potential overlap between the two risks, concerning the situation in which a subnational group might be supported by, or operating on behalf of a sovereign state. At present, I do not address this overlap.

No thefts of *fissile material* from the commercial power sector are known to have occurred.[4]

As a first cut at modeling the risk of theft, we developed a simple probabilistic model, based on the consumption of plutonium over time. Assume theft is a *binomial* event indexed by reactor-year. [5] The existing history of nuclear power might then be considered a long sequence of *Bernoulli Trials*, in which no "successes" have been observed. We consider the total history of the global nuclear industry to represent 10,000 reactor-years of experience.

In *Bernoulli Trials*, an independent *binomial* event is repeated over time. In this case the event of interest is one theft in a reactor-year. Let this event have probability, p. For small values of p the likelihood approaches certainty. If it is very unlikely that a theft will occur, then it is very *likely* that no thefts will be observed, and, analogously, if it reasonably likely that a theft will occur then it is exceedingly unlikely that no thefts will be observed. We will use the first and ninety-ninth percentiles of the likelihood to represent the plausible range of uncertainty for observing no thefts so far. For $p = 0.00046$, about 1 in 2000, there is a 1% chance of observing no thefts given the evidence. For $p = 10^{-6}$, 1 in a million, there is a 99% chance of observing no thefts.

As an aside, note that we get almost the same result, and interpretation, if we use a Bayesian updating approach on a uniform prior distribution on the probability of diversion. If we assume we no nothing about the probability of theft beforehand (p is equally likely to be anywhere between 0 and 1), then seeing no thefts yields the same confidence intervals on p noted in the preceding paragraph.

Several criticisms might be made of the simple *Bernoulli* model. Thefts are likely not independent events. It is not clear whether the probability of theft would go up or down, necessarily, depending on the lack of previous diversions. On the one hand, the industry could grow complacent over time and the probability could increase. On the other hand, potential thieves might interpret past history as indicative of the difficulty of succeeding and be less inclined to try. If we assume, on balance, that the probability of theft *increases* when no theft occurs over a period of time, then the first percentile on the likelihood of observing the evidence (1 in 2000) still provides a reasonable upper bound on the likelihood of observing no thefts. If the probability of a theft increases when none take place, then in order for us to have observed what we saw (no thefts in 10,000 reactor-years), we would have to

had to have seen an even *rarer* event then if the probability of thefts had been fixed. For a given likelihood percentile, the corresponding probability p is still a reasonable upper bound.

If, on balance, the probability of theft *decreases* over time then the likelihood may be larger than calculated. The chance of observing no diversions over 10,000 reactor-years could be higher than shown. However, the probability of diversion itself would have to be *smaller*, so the first likelihood percentile, $p = 0.00046$, still represents an upper bound, albeit an overly conservative one.

Unfortunately, similar arguments cannot be made for a lower bound, such as the ninety-ninth likelihood percentile of 1 in a million. If theft were impossible ($p = 0$), no thefts would be observed.

A more damaging criticism of the model is simply that there is little reason to assert any stationarity in p between past experience with uranium fuel and the future of plutonium fuel. The once-through cycle used in the past does not provide obvious opportunities to acquire fissile material which is directly usable. Fresh LWR fuel would require isotope enrichment to achieve a sufficient percentage of U^{235} to build a weapon. Spent LWR fuel is highly radioactive (for decades) and would require reprocessing to separate the plutonium. It may simply not have been a rewarding target. Current implementations of the closed cycle may provide a more technically attractive target for theft, mixed-oxide fuel, or MOX. MOX is not very radioactive and it can be chemically separated, fairly easily, to produce plutonium for weapons. It may be a much more rewarding target.

While this is the official U.S. view, observers abroad and in the nuclear energy field have claimed that security measures make essentially all the difference in the probability of theft and that the type of fuel cycle makes little or no difference.

Thus, using the calculated upper bound on p is suspect. There is no particular reason to suggest that the threat of MOX theft in the future is no higher than the threat of LWR fuel or spent fuel in the past. It may indeed be higher. Unfortunately, there is also no legitimate lower bound on p, except zero.

Our approach now is to consider addressing the threat risk parametrically, i.e. to treat p as a parameter of the analysis, and to consider a game-theoretic model of theft.

As a start, consider the uncertainty model for theft presented in Figure 2. In order to obtain weapon-usable material, the thieves must locate a source of the material, defeat any defenses protecting it, overcome any physical obstacles to its removal (such as mass and radioactivity) and finally, convert it into a weapon-usable form.

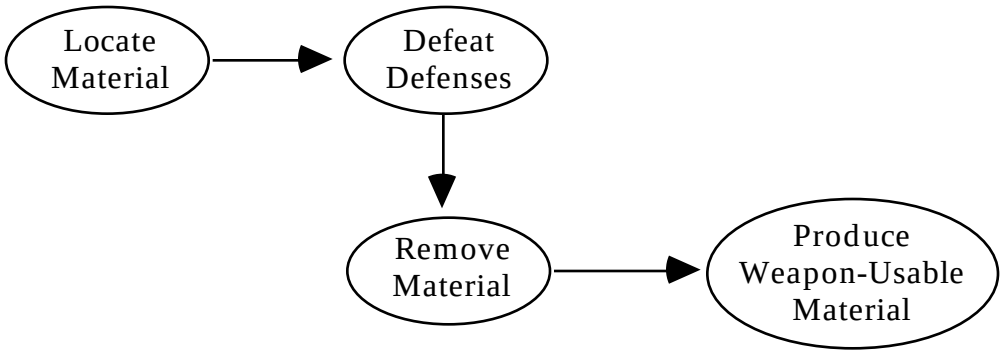

Figure 2. Uncertainty Model for Theft of Fissile Material.

Do different materials represent different risks for theft? For purposes of illustration, MOX and spent fuel might be possible targets for theft.[6] Spent fuel is more conspicuous than MOX since its radioactivity requires more sophisticated handling. This might make it somewhat easier to locate. Both are likely to be comparably defended. The primary distinction will be in the probability the thieves can successfully remove the material and convert it into a weapon-usable form. Again, spent fuel is highly radioactive and requires specialized handling. Current technology for offsite transport of spent fuel involves the use of multi-ton casks which are obviously difficult to manipulate. Once in the hands of the thieves, sophisticated radiochemistry must be used to separate out the plutonium. In contrast, the MOX fuel rods are not a comparable radioactive threat, can be individually manipulated with a forklift, and may be directly usable in a nuclear weapon. This suggests that MOX does represent a greater risk for theft, although perhaps a negligible one as compared to differences in security.

Modeling Diversion

In contrast to theft, diversion is taken to refer to the removal of fissile material from the commercial power cycle by a sovereign state for the purpose of developing a nuclear weapons *program*. We divide all states into four categories:

- Nuclear weapon states and de-facto nuclear weapons states, such as the U.S. and Israel, respectively,

- States for whom diversion is not a technologically or economically desirable way to pursue a nuclear weapons program, such as Japan, Germany, or Sweden,

- States for whom diversion may be a technologically and economically desirable way to obtain weapon material, such as Iraq, Iran or North Korea,

- States who lack the technological or economic capability to pursue a nuclear weapons program at all, such as Mali or Malta.

Only Category 3 states represent a diversion risk. Since reactor-grade plutonium is less suitable for nuclear weapons than that which can be produced directly by a dedicated reactor, a Category 2 state is likely to forego diversion, should it decide to proliferate. A category 4 state is simply incapable of pursuing a nuclear weapons program by any means.

Given that diversion is a desirable and viable proliferation option, the uncertainties associated with diversion differ from those of theft in several important respects. Consider the simple uncertainty model of a covert action such as theft or diversion as presented in Figure 3.

The chance that the covert operation will be attempted at all is obviously germane to both theft and diversion. However, assuming it has the capability, a sovereign state that decides to divert material from the commercial nuclear power sector is almost certain to succeed,[7] although perhaps not without discovery, whereas a subnational group attempting to steal material might fail through circumstance. If the theft succeeds, its subsequent discovery is probably not important to the thieves. In fact it may further their aims, if political. A summary of the relevance of the various uncertainties is presented in Table 2.

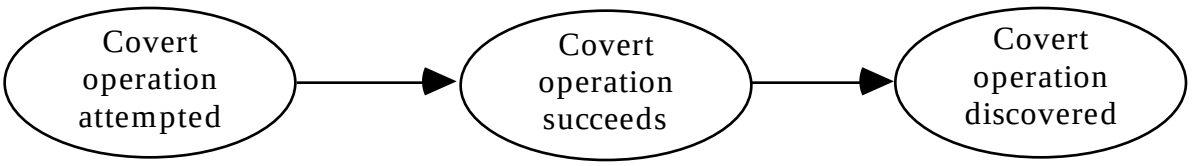

Figure 3. Uncertainty Model for a Covert Action.

Table 2. Relevance of Uncertainties to Modeling of a Covert Action.

Uncertainty	Theft	Diversion
Operation is attempted	Relevant	Relevant
Operation succeeds	Relevant	Almost certain
Operation is discovered	Irrelevant	Relevant

Because success is almost certain and the risk of discovery is important, the decision to divert takes on a game-theoretic flavor. Our study concerns a U.S. decision about pursuit of a more diversion-resistant fuel cycle. A potential proliferator will take the U.S. technology into account when acquiring a nuclear fuel cycle, and the U.S. will take into account the decisions of potential proliferators in determining whether or not to pursue such technology.

Consider a sequential game played between the United States and a single potential proliferator. The U.S. will choose a level of effort (technological, economic and diplomatic) to provide a more diversion resistant fuel cycle than would otherwise exist. The proliferator will then choose to purchase either the new, more diversion resistant fuel cycle or another alternative fuel cycle.[8] Finally, the proliferator will choose between diverting from whichever fuel cycle was purchased, and proliferating by some other means. For example, South Africa completed a successful weapons program using uranium enrichment. Iraq followed a similar approach (*inter alia*) but failed. Israel is believed to have a completed a successful weapons program using a dedicated reactor at Dimona. North Korea also followed this approach. A schematic of the sequential game is presented in Figure 4.

In this model the proliferator's choice to acquire a new fuel cycle is independent of the choice of how to proliferate. We do not consider the case in which a potential proliferator considers the acquisition of a nuclear fuel cycle solely for the purpose of surreptitiously diverting fissile material from it. We also do not consider the proliferator's decision as to whether or not to actually proliferate. This model concerns possible *supply side* barriers to the acquisition of fissile material. States of interest are presumed to have techno-economic limits to their ability to proliferate which might be overwhelmed by the choice of technology.

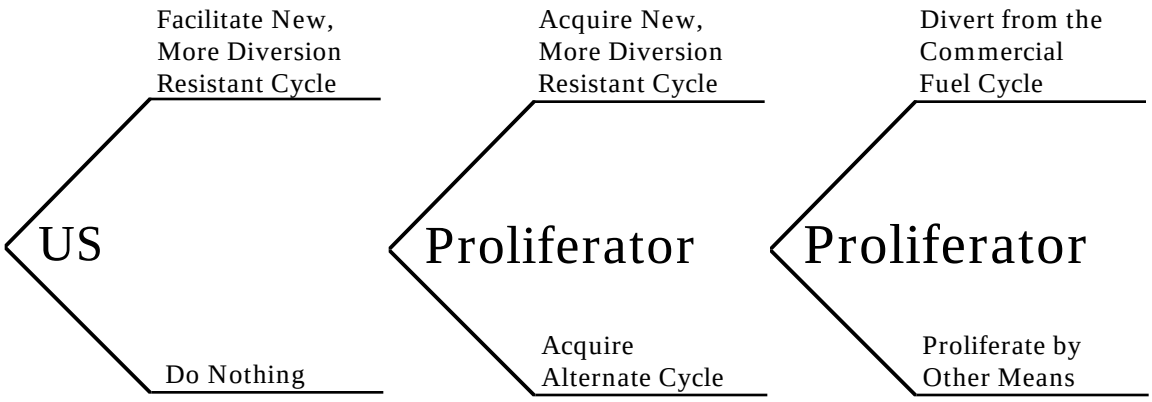

Figure 4. Diversion as a Sequential Game.

We assume that there is no uncertainty in this introductory model; that is, the game has perfect information. The proliferator's payoff includes the level of effort required to proliferate and the cost of acquiring the fuel cycle. These factors are not considered to be directly comparable. The U.S. payoff includes the level of effort involved in providing the new technology, the economic benefit derived from sale of the new technology, and the level of effort expended by the proliferator to proliferate. The more effort required on the part of the proliferator, the better the result for the U.S. The U.S. costs and benefits are considered comparable with each other, but neither is directly comparable with the value ascribed to the cost of proliferation to the proliferator.

There are three primary assumptions. First, the acquisition cost of the new cycle is a function of the U.S. level of effort. In particular, there exists some level of effort for which the new cycle becomes economically competitive with alternative fuels cycles. This effort may be zero. Second, it is more difficult to divert from the new fuel cycle than from the alternative fuel cycles. Third, we assume that the U.S. preference ordering for the various proliferation routes is exactly inverse to that of the proliferator. The more desirable a given route is to the proliferator, the less desirable it is to the U.S.

The analysis is simplified considerably by recognizing that once the proliferator has purchased a fuel cycle, it represents a *sunk cost*. The proliferator will then proliferate by the cheapest means available. Since there are three possible proliferation routes (new cycle, other cycle, other methods) there are 3! or 6 possible orderings of the costs of the various routes. The six cases fall into three categories, corresponding to the "preferred" or least-cost route: other means, alternative cycle, or new cycle. The latter category is somewhat paradoxical since the technology under consideration is supposed to be *more* diversion resistant than alternative cycles. In the near term it is unlikely that any closed cycle can be made more resistant than the once-through cycle, so to the extent that the new technology might compete with the once-through cycle this latter category is conceivable. However, it seems completely politically unfeasible since it involves the expenditure of U.S. effort to make proliferation *easier*. It is hard to imagine any amount of economic reward to the U.S. that would justify such action. We take each of the other two categories in turn.

Proliferation by Other Means is Preferred

In the first category, the proliferator considers some other proliferation route to be preferable to diversion. This route could be uranium enrichment, as pursued by South Africa and Iraq, or plutonium production in a dedicated reactor, as pursued by Israel and North Korea. In this case, the proliferator will always choose to proliferate without diverting from the commercial fuel cycle *irrespective* of whether or not the new, more diversion resistant fuel cycle exists. The U.S. decision to develop the new cycle is wholly predicated on the economic benefits associated with its sale to the proliferator.

Turning to the U.S. decision, it is straightforward that the U.S. prefers the proliferator to choose the new cycle if it is built so it can derive the economic benefit of the sale. The U.S. decision comes down to whether or not economic benefits exceed the costs (including the effort, if any, required to make the new cycle more economically desirable).[9]

Diversion from Alternative Cycles is Preferred

In the second category, the proliferator considers diversion from some alternative cycle to be preferable to both proliferation by any other means and to diversion from the new cycle. In these two cases (based on the preference ordering of the new cycle versus other means) the U.S. can actually assert leverage on the preferred route of proliferation. Consider first the case in which diversion from the new cycle is the least preferred option.

If the U.S. builds the new cycle and the proliferator purchases it, he will then choose to proliferate by some other means. If he chooses an alternative cycle, he will divert from it. Since the acquisition cost of the fuel cycle and the proliferation effort are considered noncomparable, we must use a conversion parameter to model the imputed trade-off between the two.

The U.S. prefers that the proliferator purchase the new cycle if it is developed. If the new cycle is not developed, the proliferator will purchase and divert from the alternative cycle. Is it worthwhile for the U.S. to develop the new cycle in this case? It is if the value the U.S. places on the added burden to the proliferator of having to proliferate by some other means than diversion *outweighs* the costs (less the economic benefits) of the development.

Suppose the new cycle is available. The proliferator's trade-off is then between the economic advantage of the new cycle (at some cost to the U.S.) and the added burden of proliferating via some other means if he chooses to purchase the new cycle. The level of effort required by the U.S. to make the new cycle more desirable, given this trade-off, is determined by the proliferator's choice. Assume the U.S. wants the proliferator to purchase the new cycle. The more highly the proliferator values the effort required to proliferate, the more effort the U.S. must expend to make the new cycle economically attractive in comparison to an alternative cycle. If the proliferator values the effort required to proliferate highly enough, it may not be possible for the U.S. to develop a new cycle which is sufficiently economically attractive to overcome the additional effort required to proliferate if it is purchased.

The case in which diversion from the new cycle is actually preferred over any other means of proliferation (save diversion from the alternate cycle) is analogous, except that the proliferator will choose to divert from the new cycle rather than pursue other means of proliferation.

The four cases are summarized in Table 3. There are two major results. First, if other means of proliferation are preferable to diversion, then the U.S. *cannot* influence proliferation by developing a new cycle. It can only profit economically. If diversion is preferred over other means of proliferation, then the U.S. may be able to add to the effort required to proliferate. Second, as long as there exists another means of proliferation (besides diverting from alternate cycles) which is preferable to diverting from the new cycle, then the level of effort required to divert from the new cycle is actually *irrelevant to the decision-making process*. This appears to be counter to current-thinking, which focuses on how diversion resistant the new cycle might be. This analysis suggests that as long as the new cycle is more difficult to divert from than its competitors, and that other methods of proliferation are preferable, then the current-thinking may be misplaced.

Table 3. Summary of Game Results.

Preference Ordering for Proliferation	Build New Cycle Based On	Level of Effort Required to Make New Cycle Preferred	Added Burden on Proliferator
Other means, new cycle, alternate cycle	Economic cost-benefit only	Economic desirability of new cycle	None
Other means, alternate cycle, new cycle	Economic cost-benefit only	Economic desirability of new cycle	None
Alternate cycle, other means, new cycle	Economic cost-benefit versus U.S. value on added burden to proliferator	Economic desirability of new cycle must outweigh added burden to proliferator	Proliferate by other means instead of diverting from alternate cycle
Alternate cycle, new cycle, other means	Economic cost-benefit versus U.S. value on added burden to proliferator	Economic desirability of new cycle must outweigh added burden to proliferator	Proliferate by other means instead of diverting from new cycle

Valuation of Decision Variables

Each of the variables involved in Table 3 must be estimated. The decision calculus can then be done using probability distributions, although this will complicate the analysis considerably. Using the preceding analysis, we intend to "unwrap" the games into conventional maximum-utility decision trees for both players. The proliferator's decision ultimately produces a probability distribution on

the level of effort, E^*, that the U.S. must commit to in order to make the new cycle economically attractive. The U.S. decision involves the reconciliation of the distribution on E^* with the uncertain benefits of potential sales, the value assigned to the various proliferation routes and the trade-off between proliferation and general economic concerns. We expect the final "decision" to appear as a classic probabilistic utility problem, as shown in Figure 5. In this particular example, the benefits stochastically dominate the distribution on E^*, so a risk-neutral decision-maker will authorize the project. As the decision-maker embodies a more and more risk-averse stance, the overlap (the probability that the costs E^* exceeds the benefits) becomes more important.

As an illustration of the complexity of the valuation process itself, consider briefly the value to the U.S. of avoiding a single diversion. Some past expenditures may be illustrative. The Gulf War is estimated to have cost approximately $60 billion. Addressing the Iraqi nuclear program comprised only a fraction of the total effort, so this sum could represent a conservative upper bound. The IAEA's budget is approximately $200 million per year, or $12 billion over the sixty year period of interest, assuming rate of inflation is about equal to discount rate. The present value of the oil and reactors promised North Korea if they desist from their nuclear weapons program is on the order of a few billion dollars. On the other hand, essentially no money or effort was expended to prevent Israel or South Africa from acquiring a nuclear arsenal. Thus, the U.S. willingness to avoid a single diversion is likely contained within the $0 to $60 billion range. This is a very broad range indeed.

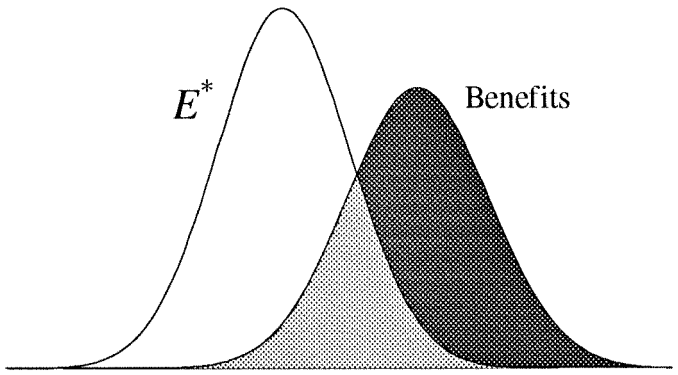

Figure 5. Example Probability Distributions for U.S. Decision.

We can also consider some order-of-magnitude numbers based on general perceptions of national interest. The world community would probably accept a one time cost of $5 billion to stop a single diversion. It would probably balk, or at least have to very seriously consider a one time cost of $50 to $100 billion. An in between figure might be $10 billion.

Conclusions

In this brief paper we introduced a decision-model for U.S. government evaluation of the development of advanced nuclear fuel cycles involving plutonium recycle. Using a highly aggregated model of the world economy we estimated that electricity demand in the next sixty years may necessitate the need for between 600 and 4500 nuclear power plants by 2060. Although it is not clear, it may be that the risk of theft of nuclear materials is related to the global use (and ubiquity) of nuclear power. We developed and critiqued a probabilistic model for the theft of fissile material based on past experience with nuclear power. We then introduced a game-theoretic model of diversion by a national actor. Using this model we demonstrated that if other means of proliferation besides diversion are preferable to potential proliferators, then the U.S. cannot influence proliferation through the introduction of more diversion-resistant nuclear power technology. If diversion *is* a desirable proliferation route, then a new cycle could force a proliferator to expend additional effort to proliferate. We also found that as long as there exists some other means of proliferation (including diversion from alternative cycles) that is preferable to diverting from this new cycle, then the actual diversion resistance of the new cycle is not relevant to the U.S. decision about whether or not to build such a cycle. Finally, we briefly discussed the valuation of the theft or diversion of fissile material.

In future work, we intend to introduce more sophisticated models of theft and of the growth of nuclear power. We also intend to incorporate some analysis of the market dynamics of new power technologies. Lastly much work needs to be done on understanding of the value of diversion to the world community as a whole, and to the U.S. in particular.

References

1. Starr, Chauncey, "Global Energy and Electricity Futures," in *Energy*, **18**(3), 1993, pp. 225-237.
2. Assuming 40% thermal efficiency.
3. Energy Information Administration, *World Nuclear Outlook 1994*.
4. Minute quantities of fissile material have been smuggled out of the former Soviet Union. The isotopic profile of these samples suggest that they originated in the former Soviet nuclear weapons laboratories.
5. An alternative might be to measure the risk per tonne stored or per tonne-kilometer shipped.
6. U.S. R&D in advanced reactor technologies is based on pyroprocessing, which involves never separating the fissile isotopes from highly radioactive actinides (such as americium-241) produced in the reactor. The material in this new closed-cycle has some of the character of spent fuel, particularly with regard to radioactivity.

7. Of course, a state may be prevented from proliferating through diplomatic means. Here we are concerned with the *differential* risk between the expected technological status quo and new technology which the U.S. might promote.
8. For example, a cycle based on PUREX reprocessing of spent fuel and MOX loading of LWRs.
9. Recall that the game models the situation with only a single potential customer/proliferator. In reality, the effort may be partially amortized over a number of potential customers.

Safeguards and Non-Proliferation for Advanced Fuel Cycles: IAEA Safeguards on Plutonium and HEU

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Abstract

During the first 30 years of existence of IAEA safeguards, no highly enriched uranium or plutonium has been routinely used in the electronuclear fuel cycle. HEU was used in research reactors and in THTR or other prototypes, and plutonium was used in critical assemblies and prototypes for the future development of fast breeders. Electronuclear use of HEU seems, nowadays, more remote than it seemed 20 years ago, whereas plutonium is entering the fuel cycle economy, not through breeders, but through the use of MOX in LWRs. The paper will be devoted to the analysis of the influence of these industrial facts on the present and future evolution of international safeguards.

Plutonium and HEU are the two "direct-use materials" in IAEA terminology. Although it is generally recognized that uranium between 20% and 60% or more, or plutonium with 20% or more of Pu 240 are not desirable for weapons manufacture, it was simpler for the Agency not to try to establish a threshold between "weapons'-grade" and non-weapons-grade materials, and to consider all of them as "direct-use." The paper will analyze the way in which such materials are safeguarded at present.

The development of the use of plutonium in the electronuclear fuel cycle, is not the only factor which leads to reconsider this situation. The prospect of weapons-grade plutonium being eventually consumed in electronuclear reactors, is another reason for doing so. Moreover the sensitivity of plutonium contained in OLR fuels, increases with cooling time. The paper should provide an opportunity for developing new safeguards approaches, best adapted to the industrial realities of the next century.

Introduction

In the early days of international nuclear safeguards, i.e., during the last thirty years or so, the basic idea has been that the presence of all nuclear materials accounted for under international safeguards should be verified in a timely fashion, in order to be able to ascertain that no significant quantity could have been diverted. Although paragraph 6.(c) of IAEA's document INFCIRC 153 provides for "*concentration of verification procedures on those stages in the nuclear fuel cycle involving the production, processing, use or storage of nuclear material from which*

nuclear weapons or other explosive devices could readily be made, and minimization of verifications procedures in respect of other nuclear material . . . ," this paragraph did remain, in practice, a dead letter up to now.

Recent events have demonstrated that such safeguards were probably not sufficient to give the necessary assurance that NPT signatories were abiding to their non-proliferation commitments. On the other hand, the resources of the IAEA being not illimited, the wisdom of systematically verifying all nuclear materials is more and more questioned. Moreover, the repeated request of an increasing number of States, for a really non-discriminatory implementation of IAEA safeguards in nuclear-weapons and non-nuclear weapons States (the principle of which is now accepted by the U.S. in the framework of the contemplated "Cutoff Convention") makes such systematic verification more and more irrealistic for the medium term future, and will necessarily lead to new safeguards approaches.

An increasing number of specialists and diplomats insist for an effective implementation of the principle of concentration of safeguards "on nuclear material from which nuclear weapons can readily be made." The development in the next century of advanced fuel cycles which will process and use so-called "direct-use nuclear materials," as well as the cooling down of irradiated fuels , which will render "direct-use materials which are not considered as such at present, are additional technical reasons for doing so. The intent of the present paper is to present suggestions in this respect.

What Are "Nuclear Materials From Which Nuclear Weapons Can Readily Be Made?"

The first practical problem is to answer this question, which is not as simple as it could seem, as demonstrated by the great confusion in the terminology used in this respect nowadays.

The IAEA recognizes a category of "direct use materials" which are uranium-233, plutonium, and uranium enriched to more than 20% in uranium-235. But this does not mean that the IAEA considers that a nuclear weapon "can readily be made" with 21% uranium.

The term "weapons-grade materials" is frequently used to designate nuclear material recognized as suitable for the manufacture of nuclear weapons, i.e., essentially plutonium with less than 7% of Pu-240, and uranium enriched to around 90% U-235.

Some are also using the term "weapons usable material" to designate nuclear material such as highly irradiated plutonium, which have never been used to manufacture nuclear weapons, but could theoretically be utilized to generate a nuclear explosion. But the term "usable" has little meaning, as all nuclear

materials, including natural uranium, are usable for weapons" after appropriate purification or isotopic enrichment.

This means that, nowadays, nobody is able to answer clearly the question "what is nuclear material readily usable for weapons" on which the IAEA is requested to concentrate its verification procedures. The first task of this paper is to try to propose a clear answer to this question.

The first element of this answer is negative: all "direct-use materials" (HEU and Pu) as defined at present are not readily usable for the manufacture of nuclear explosives.

This is easy to illustrate in the case of HEU. There is clearly no technical threshold at the level of 20% for making a nuclear explosive. Nor is it such a threshold at any other level. It is clear that a nuclear weapon can be made with uranium below 90%, and it has been reported that the South-African did so with uranium around 60%. But it is also clear that no weapon can be made with uranium at 30% or so. The reason for the choice of the 20% threshold by the Nuclear Supplier's Group, was that, at the time, no significant quantity of enrichment uranium did exist in the world between less than 10% and more than 40%. The threshold of 20% was chosen in order to avoid a "threshold effect". . . and succeeded in creating one. A category of 19.9% now exists, which is the direct consequence of the choice of the level of 20% for the definition of HEU.

But that does not mean that, if 21% uranium would exist anywhere, the IAEA should devote to such uranium more inspection efforts than to 19.9% present in the same country. Nor does it mean that the IAEA should not devote more inspection efforts to a stockpile of 19.9% uranium, than to a stockpile of 5% uranium present in the same country.

A similar discussion can be made about plutonium, with the only difference that emotional factors play in the debate about plutonium a much greater role than in the debate about uranium. It is well-known fact that nuclear weapons in Nuclear-Weapons States have been built with plutonium with less than 7% Pu-240. It is also well known that so-called "reactor-grade plutonium" produced in British gas-cooled reactors was also used to produce a successful nuclear test, but not for manufacturing weapons. It seems also that such a nuclear test was never tried with plutonium extracted from light water reactor fuels, the Pu 240 content of which is over 20%, i.e., much higher than the one of the British gas-cooled reactors at the time.

This means that, as well for uranium and for plutonium, there is probably no threshold above which a nuclear explosive "could readily be made" and below which it would be impossible. The reality is that there are nuclear materials which are clearly "weapons-grade," others which are clearly unsuitable for the manufacture of nuclear weapons, and that, between the two there is a grey area,

which needs being considered as such, with higher or lesser degrees of risk according to the composition of the material, and the nuclear fuel cycle from which it is part. The next section will be devoted to a first attempt of analysis of these different degrees.

Different Degrees of Proliferation Risks in the Fuel Cycle

Weapons grade nuclear materials (i.e., HEU and Pu of the isotopic composition which is known as having been used for the manufacture of nuclear weapons) are not only present in the nuclear arsenals of NWS, but are also present in the peaceful nuclear fuel cycles of many countries.

HEU over 40% is present in the fresh and irradiated fuels of research or demonstration reactors in many countries. Irradiated fuel from research reactors fueled with 93% uranium, still contain some 70 to 80% of U-235 after irradiation. For such fuel, as well as for power reactor fuel the protection of the radiation barrier decreases with time and finally disappears, which makes this weapons grade material readily available.

Weapons-grade plutonium is necessarily present in a part of the fuel unloaded from on-load-fueled reactors (OLR) as, during the start-up period a part of the fuel is unloaded without having achieved the design burn-up. It can also be produced because of unvoluntary low irradiation in LWRs as it happened with the Shoreham reactor. Such irradiated fuel is no more protected by the radiation barrier after some 10 years, when the radiation level at one meter falls below 100 rads/hr. It is also present in separated form in R&D facilities such as critical assemblies, which could not work in acceptable conditions with plutonium containing important quantities of americium.

This brief recollection shows that nuclear materials present in peaceful nuclear fuel cycles, can not be classified in two “black or white” categories only, if one wants to concentrate verifications on the most sensitive nuclear materials. Concentration should certainly be 100% on weapons-grade materials, but could not be zero on any nuclear material. Such concentration should be a matter of degrees, according to the many different proliferation risks associated with different categories of nuclear materials in the context of each fuel cycle.

But this is not the case nowadays, at least in theory. Officially the IAEA only recognizes two categories of nuclear materials, direct-use and not direct-use. This means, for example, that 93% HEU is not supposed to be more intensively verified than 21% HEU, or that irradiated fuel containing fuel irradiated at 30,000 MWD/t. It also means that the criteria for safeguarding metallic weapons-grade plutonium in critical assemblies, are theoretically the same as the criteria for safeguarding MOX fuel containing LWR plutonium.

Of course, this is only theory, and we can be confident that, in actual implementation of its safeguards, the Agency is differentiating its efforts according to the real proliferation risks. But it is always more difficult to implement a good practice by ignoring an unrealistic theoretical and legal basis, than by abiding to a realistic one. Moreover there is a limit to what the Agency can do without an appropriate theoretical and legal basis.

For example, it is difficult for the Agency to know if any irradiated fuel assembly contains or not weapons-grade plutonium, if the irradiation level of each fuel assembly is not properly recorded and reported. Similarly, there is no agreed procedure for inventory change reporting when, because of the cooling time elapsed, nuclear material must be transferred from the category "irradiated" to the category "unirradiated."

There seems accordingly to be a necessity for improving the theoretical approach for analysing in a more detailed manner the sensitivity of the different nuclear materials in different contexts. If one wants to safeguard efficiently the advanced fuel cycles of the next century. Failing to do so would necessarily lead to poor safeguards, as resources could not be effectively concentrated where the real risks exist.

Safeguarding Advanced Fuel Cycles

Looking thirty or forty years ahead, it seems likely that many countries in the world including, of course, NNWS, will master the whole fuel cycle, including enrichment and reprocessing, and most likely fast breeder reactors. Whether such advanced fuel cycles will also include reactors using HEU such as THTR, is an open question, but it can not be excluded. So the IAEA has to prepare itself for safeguarding increasing quantities of "direct use materials" among which military-grade materials are already present in small quantities, which will increase with the necessity of degrading surplus military HEU, and burning surplus military plutonium.

If the decision is taken to implement international safeguards in a fully non-discriminatory way between NWS and NNWS, it will be necessary to establish criteria for the concentration of inspection efforts according to the real proliferation risks presented by the different qualities of nuclear materials in the context of the different fuel cycles. It is not the ambition of this paper to present the solution to the problem, but only to suggest the kind of criteria which could be taken into consideration for the ranking of the different proliferation risks.

At the top level are necessarily weapons grade materials such as plutonium with less than 7% Pu-240 or HEU over, for example 60%, from which nuclear weapons "can readily be made."

At the bottom are natural uranium and uranium enriched below 10%, which are necessary for fueling power reactors of the present generation.

The gray area between these two categories includes many nuances of grey, from the palest to the darkest. Uranium between 20 and 30% is certainly "darker" than uranium between 10 and 20%, but although 19% uranium is "indirect use material" it would not be reasonable not to devote to it more inspection effort than to LWR fuels. Similarly, plutonium with 10% Pu 240, although not "weapons-grade" should be considered much "darker" than plutonium with 20 or 30% of Pu-240.

Isotopic composition is not the only parameter for classifying nuclear materials within one or another nuance of "grey." The "radiation barrier" is also a factor which cannot be considered in terms of "black or white." Cooling is a continuous process and the threshold of 100 rads/hour at one meter is no more a real threshold than the one of 20% for HEU. This is true for plutonium in power reactor fuel, as well as for HEU in research reactor fuel. But with time passing, the "radiological barrier" lowers and disappears, while the isotopic composition remains a critical factor.

Another important element for classifying the proliferation risks associated with different categories of nuclear materials, is the nuclear fuel cycle within which they are present. It is quite clear that the respective proliferation risks of, for example, 20% HEU and plutonium present in irradiated fuel, are not the same in countries having developed or not reprocessing or modern enrichment technologies. A stockpile of 19% uranium in a country having no reactor using such a fuel should trigger more intense verifications than a stockpile of 5% uranium in a country having LWR reactors. (To produce 25 kg of 90% of HEU out of 20% HEU with poor performance centrifuges, needs only 100 kg of 20% HEU, and two or three hundred centrifuges, which need a room no larger than this one, working during less than one year).

Building a consensus on such a qualitative scale of proliferation risk, in order to allocate in the best way inspection efforts in advanced fuel cycles, will be al long and difficult task. In order to illustrate the kind of nuances of "grey" to be taken into consideration between black and "pale grey" (nothing is white), one can suggest a scale as follows:

- separated weapons-grade HEU and Pu
- enrichment and repressing facilities
- on-load-fueled reactors
- irradiated fuel containing weapons-grade Pu (considering cooling times)
- separated non-weapons-grade HEU and Pu
- irradiated fuel containing non-weapons-grade HEU and Pu
- LEU between 10% and 20%
- LEU
- natural and depleted U

Practical Aspects

Any new safeguards approaches aimed at tailoring more realistically inspection efforts to the real proliferation risks presented by the different nuclear materials and technologies in the advanced nuclear fuel cycles of the next century, will necessarily be more "qualitative" than "quantitative". However, nuclear material accountancy and reporting, as performed at present, and the possibility of its independent verification, will necessarily remain the fundamental basis of international safeguards.

What is likely to change in the safeguarding of advanced fuel cycles, is the role of such verifications, in the overall assurance to be provided by international safeguards, about a State's abidance by its non-proliferation commitments. The request of the international community for increased transparency in national nuclear programs, as well as the readiness of many operators to make the operation of their facilities more transparent to international inspectors, give them much more effective and efficient verification tools than simple accountancy verifications. This means that monitoring of key operations in facilities, as well as monitoring of key stages of national fuel cycles, are likely to plan an increasing role in the overall inspection approach, as compared to traditional routine accountancy verifications.

The dramatic increase in the amount of verifiable information resulting from such increased transparency, as well as the request to concentrate on weapons-grade materials, will necessarily result in a change in the verification approach of the Agency. Up to now, the principle was that verifications to be performed in each facility were predetermined and more or less identical for all facilities, and that all such verifications should be performed. Such a principle is not compatible with the one of concentrating on the most sensitive materials and facilities, as it would mean that the absence or limited extent of verifications on others could be taken as granted, thus making the "unlikely" diversion routes less verifiable ... and thus more likely.

This means that the necessary concentration of verifications on the most sensitive steps of advanced fuel cycles, is necessarily linked to a new safeguards approach, in which the number of possible verifications is greatly increased as compared to traditional accountancy verifications, but only a limited part of such verifications is actually performed in an unpredictable manner. This would enable the Agency to more effectively and efficiently concentrating on the most sensitive points, without leaving open less likely diversion routes.

Conclusion

The present "black or white" classification of nuclear materials by the IAEA between "direct-use" and "indirect-use" materials seems no more relevant for the advanced fuel cycles of the next century, be it for HEU or for plutonium. A more realistic classification, including a scale with many degrees becomes necessary, as the

quantity of “direct-use material” increases every year with cooling in irradiated fuel, and weapons-grade material are returned to the peaceful fuel cycle in increasing quantities.

Such a more realistic approach of the different degrees of sensitivity of nuclear materials and technologies in the fuel cycle, should permit a better concentration of inspection effort where proliferation risks are technically greater. This, in turn, would permit a really non-discriminatory safeguards system worldwide, which many governments request for political reasons, and which the industry wishes for competitive reasons.

Self-Protection in Dry Recycle Technologies

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Abstract

In response to the INFCE conclusions, the U.S. undertook development of a new dry fuel cycle. Dry recycle processes have been demonstrated to be feasible. Safeguarding such fuel cycles will be dramatically simpler than the PUREX fuel cycle. At every step of the processes, the materials meet the "spent-fuel standard." The scale is compatible with collocation of power reactors and their recycle facility, eliminating off-site transportation and storage of plutonium-bearing materials. Material diverted either covertly or overtly would be difficult (relative to material available by other means) to process into weapons feedstock.

Introduction

An ongoing debate in the U.S. for the past twenty years has explored whether the existence and deliberate expansion of the world stock of plutonium is acceptable. On the one hand, in the 1960s and early 1970s, the projected growth in energy demand led the U.S. to plan for rapid expansion of plutonium stocks through the use of "breeder" reactors.[1,2] On the other hand, critics argued that this was unnecessary and dangerous.[3]

In 1977, the U.S. unilaterally halted its civilian plutonium separation and purification, and urged others to do the same.[4] The intent of this move was to build a major infrastructure barrier between peaceful nuclear power applications and the availability of weapons usable plutonium. Following this, a major international study, the International Nuclear Fuel Cycle Evaluation (INFCE), reviewed proliferation risks in the light of "the urgent need . . . for nuclear power [to be] widely available."[5] The study concluded that the sensitive points in the nuclear fuel cycle were: 1) stocks of highly enriched uranium (HEU) and separated (pure) plutonium, 2) enrichment facilities and their in-process product, and 3) the facilities for extraction of weapons-usable plutonium from spent nuclear fuel.

The first of these factors has recently been given fresh and urgent significance by nuclear disarmament agreements between the former Soviet Union (FSU) and the U.S. that will result in dismantling weapons containing hundreds of tonnes of weapons-grade nuclear material plutonium and highly-enriched uranium.[6] The second major concern, enrichment capability, is considered by some to now be the area of greatest safeguards vulnerability. Centrifuge technologies are now sufficiently developed and understood that a clandestine enrichment capability

could be put together in a reasonably short time and at a cost well within the grasp of a sub-national group.

The major divergence of opinion arises with regard to facilities for processing and treatment of spent fuel, the third point of sensitivity identified by the INFCE study. The traditional separations technology (PUREX) is designed to separate plutonium from uranium and thus meets the specific sensitivity criteria identified in the INFCE study. Thus, these plants and their resulting product inventories must be subject to particularly rigid safeguards. Several technologies have been specifically designed to simplify safeguarding. The high levels of radioactivity and the inaccessibility of material characteristic of dry recycle technologies not only simplify safeguarding, but also make that material less attractive as weapons feedstock than other sources that would be available to a nation seeking to undertake a nuclear weapons program.

Safeguarding the Dry Recycle Facilities

Three dry (non-aqueous) recycle technologies have been developed to the point that they deserve evaluation as potential alternates to the traditional PUREX process: the process which was developed as part of the U.S. Integral Fast Reactor (IFR) program[7-9]; the AIROX process[10-11]; and the Dmitrograd Dry process (DDP).[12-13] Each of these is characterized by a partial removal of fission products and limited segregation among the transuranic contents of the feed stream. The DDP and IFR processes both rely on a selective electrotransport of mixed transuranics, the DDP utilizing oxides and the IFR utilizing a metallic fuel form. The AIROX process is based on a partial separation based on oxide fuels by an oxidation-reduction process; at pyrochemical temperatures (400-600°C), UO_2 is converted to granular U_3O_8, and the clad and volatile and some semi-volatile fission products are driven off. The fuel is then reconverted to UO_2 and reenriched by blending or used as is for a CANDU-type reactor. None of these processes are capable of extracting a product from normal burn-up spent fuel that could be used for a nuclear weapon without extensive, complex further radiochemical processing.

The DDP is reportedly[14] the most extensively demonstrated with many thousands of fuel pins having been recycled. The Russian program has already achieved burnup data (as high at 173,000 MWd/t, or 17.3%) on more than 11,000 fuel pins (~300 fuel assemblies) of vibropacked MOX pins in the BOR-60 experimental and the BN-350 and BN-600 civilian fast-spectrum power reactors. An automated recycle/refabrication plant at Dimitrovgrad has served to prototype a potential commercial facility that could be placed at the site of the proposed two BN-800s. Development programs for waste processing and waste forms are underway.

The basic IFR processes were demonstrated on a practical scale with unirradiated fuel and on a laboratory scale with radioactive materials prior to termination of work on this technology in October 1994.

Attractiveness of Materials from Dry Recycle

Dry recycle chemistry yields a plutonium product that is inherently commingled with minor actinides (americium, curium, neptunium), uranium, and certain fission products. The minor actinides provide substantial decay heat and contamination with alpha, beta, gamma, and neutron emitters. Table 1 shows the intrinsic heat deposition rates in typical transuranic-bearing materials, which is due mostly to alpha decay of the minor actinides. The particular case illustrated is for IFR recycle, but the other processes are conceptually similar. The heating rate per gram of heavy metal (including uranium) of the spent fuel is six times that of the unprocessed LWR fuel and coincidentally about five times higher as a processed product. Even with radioactive decay, the heating rate per gram never falls substantially below the rate for the heavy metal in LWR spent fuel. Table 1 also shows that the spontaneous neutron emission rates (neutrons/s) per gram of heavy metal in the spent fuel is three times more than for heavy metal from LWR spent fuel.

The dry recycle chemistry inherently limits fission-product decontamination to a factor no greater than about 1000. A typical product composition of pyroprocessed IFR fuel is compared with a typical PUREX product from the reprocessing of LWR fuel in Table 2. Again, the results will be conceptually similar for other dry processes. From the heavy metal alone, the decay heat and spontaneous neutron emission rates are much higher in the IFR case. In addition to this, the presence of the residual fission products causes the transuranic-containing materials, at every step of the cycle, to be radioactive enough to be self-protecting due to the gamma radiation from the lanthanides. Figure 1 shows that the radiation level of the material at each step of the process easily meets the self-protection criterion of 1 W of gamma power (1 Si/h at 1 m) for the batch quantities of recycle fuels. The PUREX product for LWR recycle is necessarily very low activity. Figure 2 shows the radiation from LWR spent fuel and PUREX recycle fuel; the difference in the radioactivity of the output products is striking.

U.S. weapon designers have concluded that IFR fuel and recycle materials could not be used to make a nuclear weapon without significant further processing.[16]

Table I. Decay Heat and Spontaneous Neutron Source.

	Spent Fuel at Discharge* (Normalized to 1kg HM Basis)					
	Relative Isotopic Mass (g/kg HM)		Decay Heat (W/kg HM)		Spontaneous Neutrons (neutrons/s/kg HM)	
Nuclide	LWR	IFR	LWR	IFR	LWR	IFR
Total Pu	11.23	219.9	0.10	1.43	3380	47500
Other Actinides	1.12	3.74	2.20	10.4	1.18e+06	3.64e+06
Total TRU	12.35	223.7	2.30	11.8	1.19e+06	3.79e+06
Total U	987.7	776.3	1.48e-03	8.73e-05	1.23e+02	4.18e+00
Total HM	1000.0	1000.0	2.30	11.8	1.19e+06	3.79e+06

*Taken from Hill[15]; IFR core is a 1200 MWe fissile self sufficient core with 4 year cycle, 2 year external cycle, 100% recycle of transuranics (TRU) and 10% rare earth recycle at ~10% discharge burnup.

Table II. Normal Process Product Composition, Decay Heat and Spontaneous Neutron Source Levels.*

	(PUREX for LWR and PYRO for IFR)					
	Relative Isotopic Mass (g/kg HM)		Decay Heat (W/kg HM)		Spontaneous Neutrons (neutrons/s/kg HM)	
Nuclide	LWR	IFR	LWR	IFR	LWR	IFR
Total Pu	1000.0	219.9	9.62	4.30	3.01e+05	1.42e+05
Other Actinides		3.74		21.01		9.22e+06
Total TRU		223.7		25.31		9.36e+06
Total U		776.3		1.08e-05		5.17e-01
Total HM	1000.0	1000.0	9.62	25.31	3.01e+05	9.36e+06

*PUREX for LWR with 2 y cooling; PYRO for IFR with 100 d cooling and 2 to 1 ratio for TRU to U.

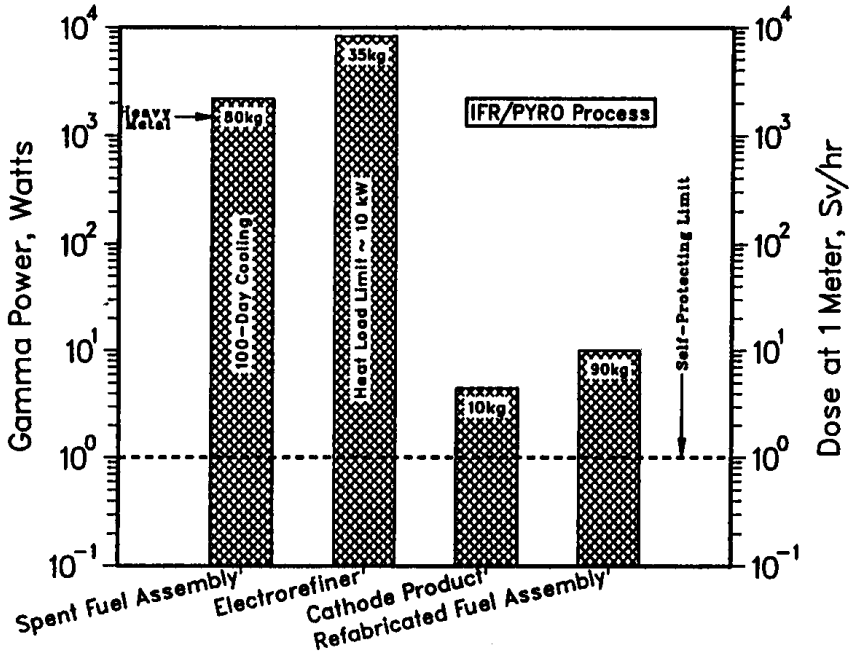

Figure 1. Dry Process Self Protection Levels.

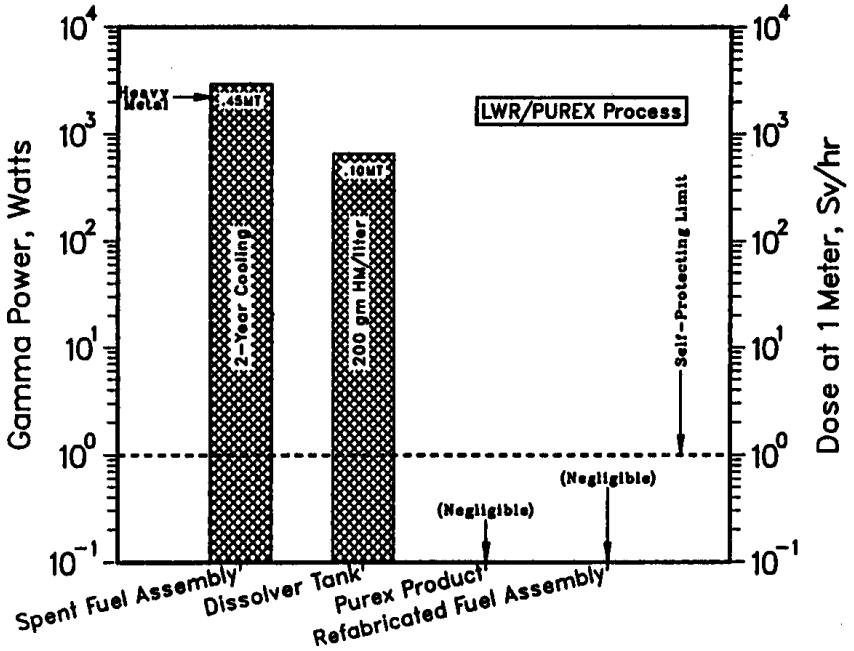

Figure 2. PUREX Process Self Protection Levels.

Attractiveness of Materials After Purex Processing

As shown in Table 3, even if dry recycle material were diverted (from any stage of the cycle) and processed in an unsafeguarded PUREX plant, the pure plutonium from PUREX processing of the diverted IFR material would have spontaneous neutron emission rates and heating rates essentially as large (within 30%) as those in the pure plutonium that comes from PUREX processing of spent LWR fuel. For weapons purposes, there is no particular significance to the somewhat higher fissile content of the plutonium that is typically recycled in a fast reactor system since the yield, yield uncertainty, and manufacturing difficulty are comparable for the two materials. In both cases, further isotopic separation would be needed in order to make highly reliable, efficient nuclear weapons.[17]

With modern technology, experts maintain that any plutonium composition could be used to produce a nuclear explosion, but it is evident that higher content of higher isotopes makes it exceedingly difficult to make a bomb. Much has been made of the U.S. tests of a nuclear weapon produced from "reactor grade" plutonium. While the actual composition of that material remains classified, the time at which those tests were performed suggests that the material was closer to "weapons grade" than to isotopic composition that would now be obtained from a commercial fuel cycle.

The possibility of loading a U-238 assembly into a reactor to make isotopically pure ^{239}Pu adds nothing to the proliferation potential that already exists with LWRs. LWR fuel assemblies are enriched in ^{235}U only to 3 or 4% versus the less than 1% enrichment in a fast reactor blanket. A nation deciding to abrogate its nonproliferation agreements has the option of short-irradiation cycles for making

Table III. Pure Pu Product after PUREX Separation.

	Relative Isotopic Mass (g/kg HM)		Decay Heat (W/kg HM)		Spontaneous Neutrons (neutrons/s/ kg HM)	
Nuclide	**LWR**	**IFR**	**LWR**	**IFR**	**LWR**	**IFR**
Pu-236	0.000265	0.0000623	0.00305	0.00108	0	0
Pu-238	9.98	6.38	6.33	3.63	26400	16800
Pu-239	553	760	1.07	1.44	12	16.6
Pu-240	221	203	1.54	1.39	201000	185000
Pu-241	173	21.7	0.671	0.0902	7.06	1.02
Pu-242	0.432	8.64+00	0.00504	0.000994	74000	14900
Total Pu	1000	1000	9.62	6.56	301000	217000

isotopically pure plutonium in any power reactor; a denial of inspector access, seizure of assemblies, and transport to an unsafeguarded PUREX process facility are all required before the plutonium can be recovered

Detection and Diversion

Dry recycle materials are intrinsically unattractive targets for diversion; physical protection is easier to provide for these fuels than for many other plutonium inventories; and inspection and accountancy techniques currently being developed and demonstrated promise to be straightforward because of the discrete (item accountancy) of the process steps.

Major safeguards against covert diversion include material control and accountancy (MC&A) and detectability. Highly enriched uranium and ^{239}Pu are comparatively difficult to detect in that active interrogation techniques are required. Detectability of irradiated materials or of reactor grade plutonium is very high due to the emitted radiation. In an overt diversion scenario, adequate shielding, confinement, and isolation are credible, but this would be very difficult in a covert scenario given access to modern detection capabilities.

Consider the diversion of a spent fuel assembly from an LWR versus that from a dry recycle facility. In both cases, the diverter would have to abrogate treaties, throw out inspectors, seize and transport a highly-radioactive assembly, and process it in an unsafeguarded PUREX facility. Independent of where in the dry cycle the material had been seized, the subsequent conversion would have to take place in a nonstandard PUREX process. Diversion from a DDR or IFR-type cycle would be particularly difficult because these fuels contain a higher fraction of fissile material, so that the front-end PUREX dissolver tank must be redesigned for more stringent criticality limits, or the input material must be blended down to a much lower fissile content. Also, the shorter cooling time used in the dry cycle leads to higher decay-heat loads and greater heat-removal requirements in the shipping casks and processing equipment, unless the proliferator is willing to wait—which would ensure timely warning. The higher radiation levels (due to the shorter cooling time and higher burnup) are more damaging to the organic chemical reagents used in PUREX reprocessing, so that a special PUREX plant for handling diverted dry recycle materials would require the reagent to be replaced more frequently. In addition, for IFR type fuels, there are additional protections associated with pyrophoricity and the incompatibility of the Zr alloying material with traditional solvents.[18,19]

Thus, the dry recycle processes have features that intrinsically avoid segregation of plutonium from uranium, minor actinides, and fission products, assuring that the dry recycle materials at every stage of the closed cycle are no more attractive for diversion than LWR spent fuel—in most cases much less attractive.

Accessibility Barriers

It is characteristic of dry recycle processes that they utilize relatively small scale process equipment. There is no major penalty in scaling the process to correspond with a power station site, thus minimizing transportation and facilitating physical security and access control. Transportation is generally a sensitive phase in any security system. On-site, such material will always be contained either inside the reactor or in the highly shielded, remotely operated, inert-atmosphere enclosure of transport casks or the hot cells in the recycle facility. It has been argued[20] that acquisition by a developing country of hot cell for remote handling of radioactive materials "may be a key proliferation issue" because "the equipment and materials used in PUREX processing would require the type of heavy shielding offered by the hot cell of a dry recycle system." This argument is specious. Modification of a system for purifying plutonium would severely interrupt normal operation and be detectable with any inspection regime. A declared, safeguarded dry recycle facility is not of concern because the conversion time following renunciation of safeguarding obligations would be extensive.

Control and Accountancy

The basis for nuclear material control and accountancy (MCA) in dry recycle technologies is different from that required by a PUREX-type process.[21] MCA is facilitated by the fact that the special nuclear material remains highly contaminated throughout the fuel cycle. Item accounting is used for fuel passing between the reactor and the collocated recycle facility. Activities in which the form and composition of the fuel are changed can be done only within the highly shielded, remotely operated recycle hot cell, which has an inert gas atmosphere and a limited number of access and transfer ports.

The batch-type recycle readily supports near-real-time MCA. Movement of material is controlled remotely with movements and weights recorded in real time by the MCA system. When material is moved from one process step to the next, it is moved as a discrete mass in a labeled container and weighed before shipment from one station and after receipt at the next station. There are no transfers involving movement of liquid through lines nor operations in which transfer valves are used. Waste and scrap also are handled as discrete, tracked, and weighed items.

For the recycle steps that involve holdup (the electrorefiner), MCA techniques appropriate to the highly-radioactive dissolver stage of conventional (PUREX) reprocessing apply. No step in the cycle requires the highly-stringent MCA and safeguards procedures that are required for the parts of the conventional PUREX cycle [including operations to fabricate mixed oxide (MOX) fuel] that involve purified plutonium.

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Perspectives for Long-Term Plutonium Utilization

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Abstract

Two decades ago, there was concern that worldwide FBR deployment rate would be limited by the availability of separated plutonium; today, reprocessing is actually limited by plutonium utilization, under some kind of "no Pu stockpiling" policy. Moreover, nuclear weapons dismantlement will constitute w-Pu stockpiles, and would raise the question of plutonium utilization even in the absence of commercial reprocessing.

From both resource conservation and safeguards points of view, the best place for plutonium is inside a reactor core. Actual experience with MOX fuel behaviour in LWRs is very promising, and the commercial operation of MELOX plant in France and, later, SMP will make the MOX cycle economically competitive. Further recycles in LWRs are possible but might become unattractive, due to Pu isotopic degradation; in the long term, fast neutron reactors are best suited for Pu utilization be it with or without breeding.

Back to the Future

Before venturing any kind of forecast, it is always useful and often sobering to revisit earlier predictions about a future which is now our present.

Twenty-five years ago, the total world electricity generation from nuclear energy amounted to 80 TWh, a mere quarter of today's French production, but expectations ran high. LWRs of both varieties, Ps and Bs were emerging as the dominant reactor type, and even though little actual reprocessing took place on a commercial and industrial basis it was almost universally assumed that plutonium recycle was around the corner, and that the next generation of reactor would be the plutonium-fed FBR. When using the expression: "fuel cycle" everybody meant "cycle," with plutonium and reprocessed uranium running in a closed loop. When you stop to think about it, the very notion of "*open* cycle" is, at the very least, paradoxical.

Two decades ago, we were in the throes of the first oil shock, President Nixon had proclaimed "Project Independence," France was launching its massive nuclear equipment program, and security of supply was a concern shared by every nation.

Official 1975 forecasts were predicting that by the end of the century more than 1200 GWe of nuclear generation capacity would be installed in OECD countries, and projections were also very high in the then Soviet empire. Feeding so many reactors during their lifetime, barring any further growth, would require more than 12 million metric tons of uranium, not far from the estimated total uranium resources of the earth, "speculative" resources included. Uranium scarcity was a credible threat, uranium price hike was a quasi- certainty. Already the new USAEC requirement to secure feed uranium 10 years in advance, a measure devised to protect U.S. uranium producers, had caused uranium prices to soar, and triggered a flurry of litigations opposing utilities to producers and plant suppliers in billion $ lawsuits.

To mitigate this threatening "uranium shock" of the nineties, the prudent policy was to develop and deploy as soon as possible uranium-thrifty FBRs and the main limitation to the rate of their deployment appeared to be availability of separated plutonium. Such was the future seen in 1975.

As a matter of fact, technology appeared ready for this policy to be implemented: the oxide head-end HAO of the UP2 reprocessing plant was nearing completion at La Hague, the first two fast neutron breeders of significance, PHENIX and PFR, had started operation, SNR 300 was under construction, to be followed by CLINCH River, SUPERPHENIX and MONJU. In the U.S.A, the "GESMO" (generic environmental statement on mixed oxide fuel use) proceedings were paving the way to a policy of significant plutonium recycle in LWRs, a path also followed by Germany.

But more ominous events were also happening. The first rash of plants cancellations was plaguing the United States, where the West Valley reprocessing plant was definitively shut down, and construction was abandoned on the Morris plant. In addition, the 1974 Indian nuclear explosion had reawakened widespread concerns about the risks of nuclear weapons proliferation.

The ensuing years brought as many setbacks to the optimistic nuclear vision of 1975: U.S. utilities went on canceling plants faster than the rest of the world was ordering new ones; President Ford canceled GESMO and in 1977, President Carter deferred "indefinitely" civilian reprocessing and breeder development. We went then through the year-long "INFCE" (International Fuel Cycle Evaluation) happening, during which both supporters and opponents of the plutonium recycle stood their ground.

Then occurred the 1979 mishap at Three Mile Island and, in its wake, the first serious questioning of the safety of nuclear power. Year, after year, the forecasts of nuclear deployment were revised downward. The Chernobyl catastrophe extended worldwide this trend, which previously had been a mostly American syndrome.

Elected in 1980, President Reagan lifted his predecessors' ban on civilian plutonium use, but he did little more to revive the nuclear option in the U.S.A and did not prevent the demise of the Clinch River demo-FBR.

How do we stand today, as far as plutonium utilization is concerned? On the one hand, huge LWR commercial reprocessing plants are operating in La Hague (UP3 and UP2-800) and Sellafield (THORP), and another one is under construction at ROKKASHO Mura. These plants recover plutonium and reprocess uranium from spent PWR and BWR fuel elements belonging to a dozen countries and condition the residual wastes.

On the other hand, we know with certainty that the total world installed capacity at the turn of the century, that is five years from now, will barely reach 400 GWe, a far cry from the '75 expectations. As a consequence, uranium *is* cheap and *appears* abundant. Under such circumstances, and based on uranium availability, FBR deployment is not urgent and certainly not limited by any plutonium shortage. On a pure economical basis, and with current uranium prices, FBRs cannot compete with well proven and mass produced LWRs, even though the latest evaluations of the EFR (European Fast Reactor) project did show extremely significant cost reductions as compared to Superphenix!

We are no longer threatened by a penury of separated plutonium, while stockpiling excess plutonium makes little sense: Americium 241 build-up progressively complicates further Pu use, and physical accountability and protection measures are very expensive. Whether officially expressed or not, *a "no excess plutonium"* policy is rapidly spreading.

The latest development worth mentioning, a very significant one, was the end of the cold war, symbolized by the November 89 fall of the Berlin Wall. With this momentous event, the Superpowers actually started retiring nuclear weapons from service, dismantling the warheads, and therefore stockpiling recovered weapon-grade plutonium (w-Pu) in quantities which will soon become very significant. Even a country like the United States of America, today committed again to a no-civilian reprocessing policy, is faced with the problem of plutonium utilization.

To Burn, or to Bury? That is the Question...

Without undue reference to Aesop's tongue, plutonium is, at the same time, a precious energy resource, a radiotoxic substance which must be handled carefully, and fissile material which must be accounted for and protected against diversion.

As an energy resource, 1 gramme of plutonium is worth over l metric ton of oil. Burning the plutonium is our indirect way to burn uranium 238, and the stakes here are high: used in "open cycle" LWRs, uranium resources are of the same order of magnitude as oil or gas resources (Fig. 1), while used in fully recycling FRs, the

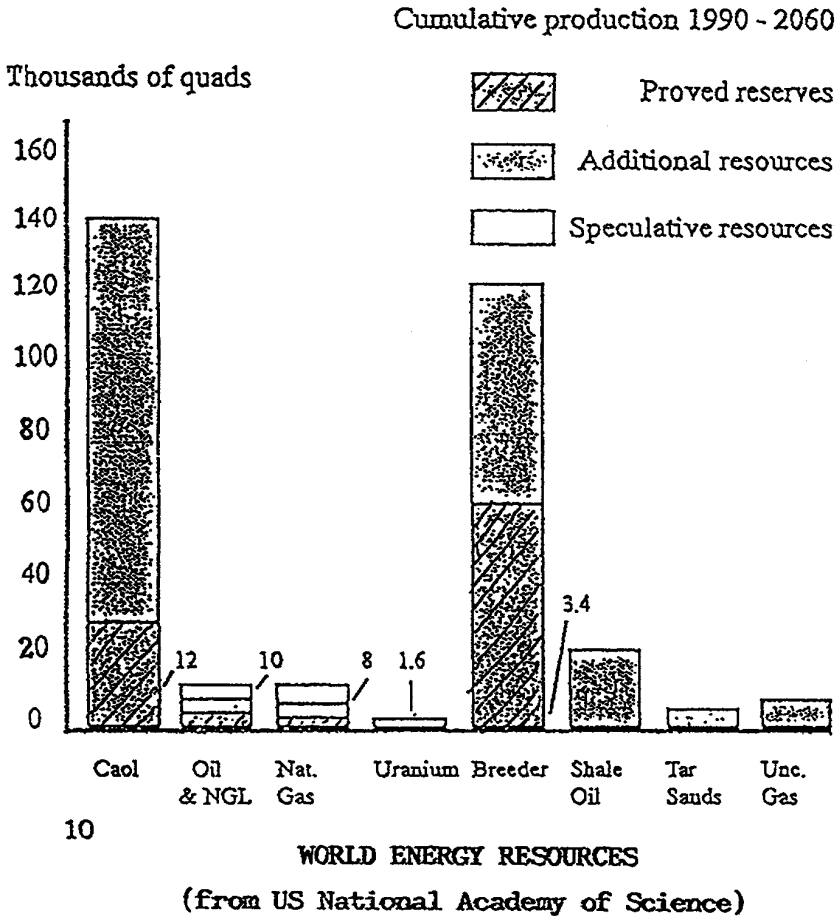

Figure 1. Cumulative production 1990–2000.

same resources are comparable to coal, the major fossil energy resource present in the earth crust.

The radiological dangers of plutonium are well covered in a number of papers (see, for instance Refs. 1 and 2) but let me focus on one specific issue. After the first 1000 years or so, when most of the fission products have decayed below significance, plutonium constitutes more than 90% of the radioactivity and the radiotoxicity of the spent fuel, and it is therefore probably the main obstacle to public acceptance of high level wastes (HLW) burial (Fig. 2 and Ref. 4).

It has been said that, given the spread of knowledge about nuclear physics and the computing power available today on anyone's desktop, the only real barrier against the proliferation of nuclear weapons is the unavailability of highly concentrated fissile materials. This is probably true, at least as far as crude devices are concerned. Hence the fear raised by recent stories of fissile materials smuggling. Even though commercial grade plutonium is not, and by far, as sensitive as

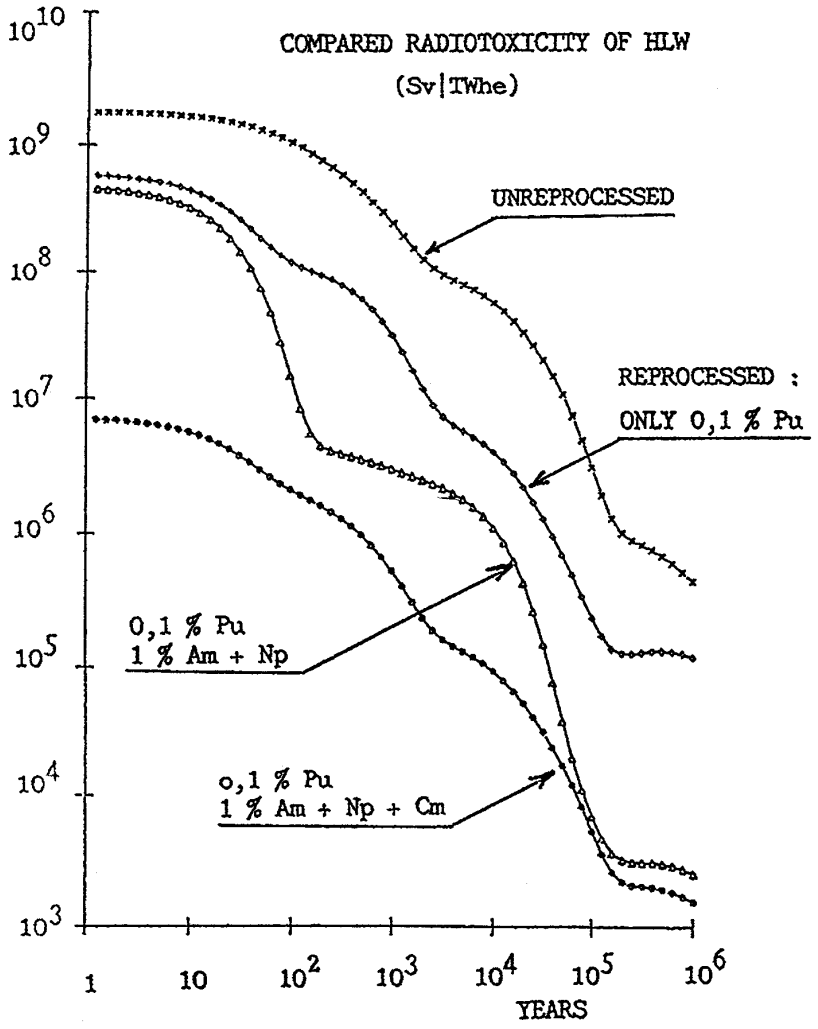

Figure 2. Compared radiotoxicity of HLW.

w-plutonium, separated plutonium must be kept under stringent safeguards and adequate physical protection.

For a fissile substance you want to be as inaccessible as possible, the best place is inside a reactor core . . . And wishing the plutonium away will not work.

All 430 or so nuclear reactors generating electricity throughout the world use uranium bearing fuel and therefore produce plutonium. Any typical 1000 MWe LWR is fed with 3.2 to 3.7% enriched uranium, and produces in excess more than 200 kg of plutonium every year. This fact shall not disappear unless you shut down every nuclear power plant and even then one would be faced with a huge amount of plutonium already produced, of the order of 1300 metric tons (not to mention the w-Pu).

Switching from the uranium to a thorium based fuel cycle would change the *vocabulary* and not the problem. Uranium 233, an excellent fissile material, would offer the same risk of diversion for explosive purposes than does plutonium 239, and we would have to ponder the comparable (or even higher) long term radiotoxicity of the thorium cycle to that of the uranium fuel cycle. We may well have, some day, to turn to thorium 232 to supplement uranium 238 as a fertile material and incur the cost of developing a new fuel cycle on an industrial basis, this will not significantly alter nor alleviate the dilemma we face. Plutonium is here, more and more so, and we must either use it (now or later) or dispose of it.

Burn the plutonium, or bury it. There is no third road in the long term. Of course, one may choose interim storage of spent fuel elements under appropriate safeguards, and for a number of countries, it appears to be the present choice. But it is only a choice for the short term, which inevitably leads to a continuous increase in plutonium, unreprocessed plutonium, stockpile. At the end of the interim period, it shall still be: burn or bury.

We have already underlined the drawbacks of the burial scheme. Waste of natural energy resources and need to demonstrate the safety and leak-tightness of the underground repository over very long periods, under normal or abnormal conditions. But if burying unreprocessed spent fuel elements, with their full content of plutonium and minor actinides, proves to be generally accepted by the public and the licensing authorities, it will surely not be necessary any longer to go to extreme lengths to remove minute plutonium traces from reprocessed HLW. This could significantly simplify the reprocessing process and should therefore reduce reprocessing costs.

On the other hand, reprocessing and plutonium recovery make only sense if the plutonium is then recycled without delay.

State of the MOX Art

Today, 85% of the world nuclear plants are LWRs (PWR, BWR and VVER). It is thus in LWRs that plutonium is mostly used today and used as mixed $(U,Pu)O_2$ called MOX. A very comprehensive perspective on MOX recycle can be found in Ref. 3.

As early as 1959, a program of MOX insertion was started in the BR2 12 MWe PWR of Mol, in Belgium. In the late 60s and early 70s, MOX assemblies were loaded in U.S. (San Onofre, Quad Cities, Dresden, etc.) and Japanese (Mihama) plants and some others. Today, the largest plutonium recycle programs are carried out by Germany and France.

Germany started in 1972 loading MOX in KWO (Obrigheim), but launched a significant program in 83-84 only. Seven German plant use MOX fuel, and the three KONVOI PWR are licensed for the irradiation of up to 50% MOX assemblies.

The French Pu recycle program started with a first reload including 30% MOX assemblies in the 900 MWe PWR St Laurent B1 in 1987. About 16,900 MWe units are, today, licensed for operation with 30% MOX reloads, beyond those, 12 additional units are technically ready to do so when authorized, and seven reactors are actually operating under such a scheme. Details on Electricitè de France (EdF)'s plutonium management policy can be found in Ref. 5. The MOX subassembly is the standard Fragema AFA design. The cores are managed according to a "Hybrid" scheme where MOX assemblies remain during three cycles while 3.7% enriched UO_2 assemblies stay during four cycles. When MOX irradiation is authorized up to 45 GWd/t, this scheme will be simplified. Experience has been accumulated over more than 20 reactor-years, with 320 MOX assemblies loaded. This operational experience has proven very positive.

EdF plans to recycle in its 900 MWe PWRs all the plutonium recovered in UP2-800, minus the amount needed for Superphenix, and this is compatible with the output of the Cogema's MELOX plant. This 120 t/y fabrication plant has started operating in Marcoule and very smoothly. To complete this survey of the "state of the MOX-art,: let me add two precisions:

First, quoting from Ref. 5, "The economic balance of MOX/UO_2 has been reached through the operation of hybrid core management. It would be reasonable to assume that MOX PWR fuel will benefit from the experience gained when irradiating UO_2 fuel. Therefore, despite the present low cost of natural uranium, MOX PWR fuel will no doubt supplant UO_2 fuel from a cost point of view."

The second point worth mentioning is that the feasibility of reprocessing irradiated MOX fuel under the standard PUREX process has been demonstrated by Cogema on an industrial scale during a demonstration campaign of 4.7 metric tonnes in 1992.

Beyond MOX, Burn or Breed

Plutonium recycle in LWRs has a number of advantages. It is feasible today on a routine industrial basis, it is roughly competitive with enriched uranium, it saves natural resources, it avoids accumulating plutonium inventories (a 30% PWR MOX reload has a zero net plutonium balance), it provides a very good protection against diversion as soon as loaded in reactor. One can add that recycling w-plutonium in LWRs would allow to lower its grade to commercial while producing power, a scheme much less far-fetched than tainting fresh w-Pu with fission products.

But LWR Pu recycle has its limitations which make it a medium term solution, but not a truly long term one. Successive recycles in reactors with a thermal neutron spectrum continuously lower the isotopic grade of the plutonium, leading to the necessity to increase the total Pu(U+Pu) ratio, and we know that there is a limit to this ratio, over which the void coefficient in PWR would no longer be negative in all circumstances. In addition, successive recycles build up inventories

of minor actinides, neptunium and americium, the long term radiotoxicity of which is significant (if plutonium is removed and burnt).

One recycle is attractive, be it only because it leads to interim storage of only 1/8th of Pu bearing irradiated spent assemblies. A few recycles ("oligorecycle") are feasible, especially under schemes where recycled Pu would be mixed with "fresh" Pu from UO_2 reprocessing, but they may prove economically unattractive. True *multi*recycle seems today out of the question.

This is why we believe in the future of fast neutrons reactors (FRs) even before we need their breeding abilities to extract the full energy content of uranium.

Owing to a more favorable fission-to-capture cross section ratio, FRs can burn degraded plutonium, no longer fit for LWRs on a true multirecycle basis, and even contribute to the fission of minor actinides if this is deemed desirable for HLW disposal. Assessing with some degree of certainty these FR capabilities is the objective of the CAPRA international program launched by France in mid-1993, and whose precise description is out of the scope of this paper (see for instance Ref. 6). As part of this program, which includes numerous core studies and extensive experimental validations, a CAPRA subassembly using reprocessed Pu from irradiated MOX fuels will soon be loaded in Superphenix.

Around 2005, we shall have demonstrated the full flexibility of FRs to accommodate various plutonium management policies, as well as we know today their aptitude to breed. From then on, the proper choice between breeding and burning will be made taking into account what will be the general energy and nuclear context. But FRs or FBRs will only be deployed if reprocessing is still an industry at the time, which implies that LWR MOX recycle is first implemented on a wide basis.

The alternative is plutonium accumulation and massive burial.

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How the United States Can Harmonize Its Internal Conflict Over the Nuclear Fuel Cycle

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Abstract

This paper examines the underlying reasons for the current impasse existing in the U.S. regarding nuclear fuel cycle policy, and proposes actions to shift U.S. fuel cycle policy to meet both non-proliferation and domestic energy security concerns. Three near term actions are suggested: (1) a program to convert weapons plutonium to MOX fuel for consumption in existing water reactors; (2) reexamination of the safety and fissile material security of the direct disposal option; and (3) a program to encourage dry recycle of spent fuel into existing water reactors, without separation of fissile materials from the fission products.

Introduction

As the largest producer of nuclear electricity in the world, and as the country which originally brought both the energy and weapons potential of uranium and plutonium to the world scene, the United States has a responsibility to provide leadership in applying this energy source safely and carefully to meet both the energy needs and environmental needs of its citizens, while at the same time assuring that it is not used by others for weapons purposes.

In the last twenty years, it has not exercised this leadership. Since its turn away from a closed nuclear fuel cycle to a direct disposal approach, in the mid 1970's the U.S. has become increasingly impotent in its ability to influence the use of nuclear energy in the rest of the world. The growing independence of States in sensitive regions of the world with respect to nuclear energy is evident. Of even greater concern, under the present course of direct disposal, the U.S. appears to be foreclosing the continued use of this environmentally benign energy source to future Americans.

Polarization of Fuel Cycle Views in the U.S.

The debate over the proper course for the U.S. nuclear fuel cycle has become increasingly polarized. This polarization stands in the way of any lasting resolution

of the conflict. Both sides defend their position with religious fervor. A compromise is necessary if we are to have a chance of solving this problem.

The authors believe that a compromise is possible. However, to change course is not easy, especially when the subject is a national policy having both international and domestic energy security implications. Therefore, we believe the proper immediate action is to take actions to allow the U.S. to PAUSE while it examines the future direction that best meets the needs of both sides. The Interim Storage Facility mandated in pending legislation is exactly the kind of action that allows such a pause.

The main object of this paper is then to show how such a PAUSE can indeed lead to harmonization of the polarized views, and a future course which solves both the international non-proliferation as well as the domestic energy security issues.

The Current Approach: The Direct Disposal Fuel Cycle

Our present course remains one which treats spent fuel, including both its fissile and its fertile content, as a waste, to be eventually disposed of directly in a geologic repository. Neither the utility industry, nor the Federal Government have any existing infrastructure, or ongoing development plans, to recycle this fuel or otherwise process it, prior to disposal. The arguments for those who favor continuation of this course, and those who oppose it, are summarized as follows:

The NP's (No Plutonium)—Those who favor continuation of the present course, base their arguments on:

- The economics of reprocessing is unfavorable. The cost of recycling in Fast Breeder reactors remains prohibitively high.

- Reprocessing creates large quantities of liquid radioactive wastes which must be treated and disposed of. It also adds to the radiation exposure of workers.

- There's plenty of uranium, much at low cost, to sustain nuclear energy for many decades. By mid-century, there may be other sustainable energy sources besides nuclear.

- It's best not to separate plutonium from the uranium and fission products; it's too easy to divert to weapons use.

- Fuel pools are filling up. It's important to transport the spent fuel to interim storage and concentrate on getting the U.S. repository designed, licensed and in operation. We can wait till later to consider reprocessing and recycle. Meanwhile, if use of nuclear power is to survive in the U.S.,

we must show the public that we can follow through with our program of direct disposal.

The RC's (Recycle Spent Fuel)—Those who favor a return to the early seventies, in which U.S. policy, and industry infrastructure, were both aimed at closing the fuel cycle, reprocessing, using MOX fuel in water reactors, and continuing development of the fast breeder reactor. The RC's argue:

- Economics of reprocessing is a matter of supply and demand. When uranium demand exceeds supply, reprocessing will become economic compared to alternatives. Timing is a commercial matter and not to be prescribed in a free market.

- The ultimate safety of nuclear waste disposal will be enhanced by reprocessing, since the more hazardous wastes can be separated and immobilized in a more secure manner. Transmutation is also possible.

- Nuclear remains the only long term solution that can meet our domestic (and worldwide) energy needs without the potential for unacceptable damage to the biosphere. Only recycle will permit use of nuclear in the long run since supply constraints will eventually prevent the continued use of uranium on the once through cycle.

- Plutonium can be protected against diversion for weapons programs, provided:

  - We strengthen the IAEA safeguards regime so signatory countries cannot cheat.

  - We maintain an effective multilateral nuclear export control regime requiring full scope safeguards as a condition for nuclear export.

  - Continued progress in resolving regional conflicts allows the non-signatory countries to join the NPT.

  - Weapons states make real progress in further disarmament, and in particular begin to demilitarize dismantled nuclear weapons including plutonium.

- Unless the U.S. allows the non-nuclear weapons states access and help in peaceful nuclear technology, and in particular allows freedom of choice with respect to recycle of their spent nuclear fuel, they will seek other partners for nuclear cooperation and recycle anyway. In Asia, other partners would include Japan and China, both of whom have capability for reprocessing and supporting recycle programs in other Asian countries.

Our Current Failure to Search for a Middle Ground

The authors believe that these two sides (the NP's and the RC's) are becoming so entrenched in their positions that there is no real search for a middle ground. The NP's see no real reason to compromise; after all the current U.S. course is consistent with their position. Never mind that it has not succeeded in changing the situation overseas. Never mind that the safety and security of permanent geologic disposal of large quantities of plutonium and fission products has come into question.

The RCs are equally entrenched in their position. Anyone who talks of compromise, and alternative fuel cycle futures other than complete reprocessing, is considered a traitor.

It is not too late to find a common position. By striving for a common position, both sides can come much closer to achieving their objectives than is possible if each side sticks to its present course.

Why the NP's Lose If We Stick to Our Present Course

The evolution of the world wide non-proliferation regime, with increasing dependence on using the energy value of plutonium, provides direct evidence that under its present course, the U.S. will become increasingly impotent in effecting world use of plutonium. Let us take a brief look at that history. The evolution of U.S. international policy towards the peaceful use of nuclear energy can be viewed in five distinct periods, starting with a "secrecy" period immediately after World War II, arriving at the worldwide accumulation of plutonium stage which exists today. The following briefly characterizes each of these phases:

1. Secrecy (1946-1953): Recognizing the enormous destructive force of the atom bomb, the victorious Allies agreed that international controls would have to be put into place before information related to peaceful applications of atomic energy could be transferred. In June 1946, the U.S. presented the Baruch Plan, a daring but ill-fated proposal that called for the transfer of all potentially-dangerous atomic energy activities to a new international authority, followed by the destruction of all existing nuclear weapons. As mandated by the Atomic Energy Act of 1946, the U.S. closed down its wartime collaboration with the UK and Canada and pursued a policy of secrecy and denial.[1]

2. Promotion of Peaceful Atomic Energy, under Safeguards (1953-1974): By 1953, it was clear that the efforts to shroud the technology of nuclear fission in secrecy was failing. The USSR and the UK had successfully tested nuclear explosive devices, and American firms were being held back from competing in the incipient market for nuclear power technology. President Eisenhower's "Atoms for Peace" address in December 1953 signaled the start of a new era of nuclear cooperation and institution-building. Bilateral nuclear cooperation agreements were concluded with

developing as well as industrialized countries. Safeguards agreements were negotiated to assure that nuclear materials and technology being transferred could not be diverted to weapons use.

Many technical approaches to nuclear power generation were being explored and developed. Underlying this activity was a common understanding of how the nuclear fuel cycle would evolve. Although the first generation of nuclear power reactors would be based upon uranium, it was widely feared that exploitable uranium deposits would be quickly depleted. Believing that the next generation of reactors would be increasingly based upon plutonium, many countries began to investigate reprocessing and recycle technologies.

After France (1960) and China (1964) joined the "nuclear club" and concern deepened over the prospects of further nuclear proliferation, the U.S. gave its support to the establishment of a strong nonproliferation regime based on the Nuclear Non-Proliferation Treaty (NPT). The negotiations leading to the NPT, which entered into force for a 25 year term in 1970, reflected not only the widespread desire to prevent further proliferation. A second basic and complementary objective was to establish a firm legal underpinning for the right of all Parties to the NPT to develop and use nuclear energy for peaceful purposes. This second objective was of critical importance to the industrialized Non-Nuclear Weapons States which were developing nuclear power programs. Germany, for example, emphasized that no nuclear activities for peaceful purposes could be prohibited. U. S. negotiators accepted this interpretation, and agreed that neither uranium enrichment nor the development, under safeguards, of plutonium-fueled power reactors would violate the NPT.[2]

3. Controls over Sensitive Technologies Tightened, as Proliferation Concerns Deepen (1974-1981): Following India's peaceful nuclear test in 1974, the U.S. responded with a series of initiatives to strengthen the international nonproliferation regime. The first steps were taken to persuade the other principal nuclear suppliers to establish a voluntary set of guidelines on the terms and conditions for nuclear trade, and to place barriers on exports of sensitive technologies and facilities. Publicly-funded R&D programs supporting the development of reprocessing and breeder reactors came under attack in the Congress. The Ford Administration undertook a major review of U.S. nuclear energy and nonproliferation policies, which led to a decision to slow down the production of separated plutonium until an effective international regime of safeguards and nuclear export controls was in place.

The tentative steps taken by the Ford Administration to ease back on fuel recycling programs were pursued with far more force by President Carter. The NRC was persuaded to halt a nearly-completed study evaluating the licensability of reprocessing (GESMO - Generic Environmental Statement on the Use of Recycled Plutonium and Mixed Oxide Fuel in Light Water Cooled Reactors). The fast breeder prototype reactor program was canceled, and construction of a commercial

reprocessing plant in Barnwell, South Carolina, was brought to a halt. This shift in U.S. policy was made clear in President Carter's opening remarks at the organizing conference for INFCE (International Fuel Cycle Evaluation) in October 1977:

"I have the feeling that the need for atomic power itself for peaceful uses has perhaps been greatly exaggerated. And I hope that all nations represented here and others will assess alternatives to turning to this source of power . . ."[3]

4. Carrots and Sticks (1981-1992): Under President Reagan, U.S. policy moved from a stance of prohibiting fuel recycling to that of encouraging the once-through fuel cycle. The Nuclear Waste Policy Act of 1982 committed the Federal Government to build a permanent geologic depository for spent fuel and to accept spent fuel from U.S. utilities starting 1998, thereby relieving them of the responsibility for the back end of the fuel cycle. Programs looking to the eventual use of plutonium fuel were no longer prohibited. The Department of Energy continued the breeder reactor R&D program on a reduced scale. The U.S. ceased its efforts to dissuade other advanced nuclear countries to abandon their fuel recycling programs. In a move that came under considerable fire, the U.S. assisted Japan to establish a secure passage for the return of plutonium from spent fuel reprocessed by France, for use in making MOX to fuel Japanese reactors.

The Reagan and Bush Administrations also took steps to close what were regarded as weak areas in the international nonproliferation regime. Key nuclear threshold states (Argentina, Brazil, South Africa), were brought into the NPT as were the two remaining Nuclear Weapons States (China and France). By offering research cooperation combined with threats to stop furnishing HEU fuel, the U.S. sought to persuade other countries to convert their research reactors to LEU. Under U.S. prodding, the Nuclear Suppliers Group agreed to control exports of nuclear technology, and, in fulfilling a long-standing U.S. objective, to accept full scope safeguards as a condition of supply.

5. Plutonium Accumulation (Civil and Military) Grows Rapidly (1993–): The Clinton Administration has pursued the contradictory goals of reducing both the use and the accumulation of plutonium. In announcing U.S. nonproliferation and export control policy in September 1993, President Clinton said that the U.S. would seek to eliminate where possible the accumulation of stockpiles of HEU and plutonium and that it would explore means to limit the stockpiling of plutonium from civil programs. He also said that the U.S. would propose a multilateral cut-off convention on production of HEU or plutonium for nuclear explosive purposes, and that the U.S. would initiate a comprehensive review of long-term options for plutonium disposition. President Clinton made clear that the U.S. did not encourage the civil use of plutonium, but he also affirmed that the U.S. would maintain its existing commitments regarding the use of plutonium in civil nuclear programs in Western Europe and Japan.

Other policy actions were taken to reinforce the once-through fuel cycle. Funding for the fast breeder development program was eliminated. At the same time, the timetable for achieving the once-through fuel cycle was being undercut by the prospect of further delays in characterizing Yucca Mountain, Nevada as a possible permanent geologic repository.

What Has U.S. Policy Achieved?

Despite the many shifts in U.S. nuclear policy and programs, U.S. presidents have been steadfast in regarding the prevention of further proliferation as their over-riding goal. The U.S. took the lead in international efforts to set up an international structure of agreements and institutions centering upon the NPT and the IAEA, which has sharply constrained the proliferation of nuclear weapons while also providing a base for peaceful cooperation in use of nuclear energy. More recently, institutional and technological means for dealing with renegade states, in particular Iraq and North Korea, has been made more effective.

The durability and effectiveness of this structure over the long-term depends upon the dovetailing of interests of the countries involved. A commonalty of interests among countries with advanced nuclear programs underlies the cooperative programs (e.g., the Nuclear Suppliers Group) to control the export of nuclear weapons material and technology as well as in dealing with emerging threats such as the risk of smuggling of nuclear material from the CIS region.

In addition to forging a cooperative institutional and legal framework, the U.S. has worked very hard, following India's nuclear test, to suppress the use of sensitive nuclear materials and technologies. While other advanced nuclear countries have joined the U.S. to control the export of sensitive materials and technologies, they have seen no reason to place their nuclear energy policies in conformity with that of the U.S.[4] They have pointed to their treaty right, clearly established by the NPT, to the development and use of nuclear energy. Despite U.S. pressure, many EURATOM countries including France, the UK, and Switzerland, continue to rely on reprocessing as an integral part of their nuclear fuel cycle programs. Japan is exploring plans to form a common nuclear energy community with other Asian countries, called ASIATOM, in which Japan may offer fuel recycling services on a regional basis.[5] Although President Clinton has declared that the U.S. will maintain its existing commitments regarding the use of plutonium in civil programs, uncertainty over the future course of U.S. policy has often hindered nuclear cooperation with these countries.

While not halting the reprocessing programs of other advanced nuclear countries, U.S. opposition has slowed their expansion. U.S. attitudes have also influenced the decisions of Germany and others to forego their own repressing programs. Since no country has succeeded in starting up a permanent geologic repository, the slow-down in reprocessing and recycle programs has resulted in growing stockpiles of civil plutonium worldwide.

Compounding this accumulation of civilian spent fuel, successful arms control efforts have led to the increased accumulation of weapons grade plutonium from dismantled nuclear weapons. Over 100 tonnes is expected to become available from the weapons to be dismantled by the U.S. and Russia under the START treaties. The U.S. National Academy of Sciences has called this a clear and present danger.

A New Direction for U.S. Policy: Harmonizing the NP's and RC's

The tensions resulting from the conflicting policies of the U.S. on one hand, and other advanced nuclear states on the other, threaten to weaken the commonality of interests, and of programs, to reduce proliferation risk. With Japan giving serious thought to establishing an ASIATOM, there is a more likely prospect that the advanced nuclear states will break apart into blocs—North America, Western Europe, CIS, and Asia. U.S. influence would decline further, and it would be far more difficult to advance U.S. nonproliferation goals.

It is clear that the NP's must seek a pause, and a new direction, if the U.S. is to have any influence at all on the safeguarding the worlds growing stockpiles of plutonium. If the U.S. succeeds in gaining a pause in its path towards direct disposal, as would result from enactment of pending legislation, then what action can the U.S. take to find a common ground, and make this indeed a turning point to a new direction? Here are a few suggestions on how to use this pause most effectively, and what that new direction might be.

Suggestion 1—Convert Excess Weapons Plutonium to MOX Fuel: the U.S. and Russia can both proceed expeditiously to demilitarize their excess weapons plutonium and turn it into useful MOX fuel for commercial reactors. The NP camp will have to compromise their "no plutonium" policy, but this plutonium already exists; it is not a matter of separating new plutonium. Approval of this course would help set the stage for a rational debate over the question of civil plutonium. And because of the energy produced, it would not overwhelm the budgets of the weapons states. Even more important, it would demonstrate to Non-Weapons States that they can utilize already safeguarded separations and fuel production facilities in advanced nuclear states to help them gain energy value from their spent fuel, without having to install their own separations plants.

There are many acceptable proposals on the table to achieve this MOX fuel use in the near future. What is needed is the will by Russia and the U.S. and later the other Weapons States to actually do it. An example is the Canadian proposal to convert U.S. excess weapons plutonium to CANDU MOX fuel for use in Ontario Hydro's Bruce Station within 15 to 25 years. This program can begin in four years at a relatively modest cost . . . under $100 million per year. Other proposals are also attractive. In addition to the immediate problem of disposing of the plutonium, such an action by the U.S. and Russia would set the stage for a less dangerous fuel cycle regime in many of the emerging nuclear nations such as those on the Pacific

rim. Such countries would be able to depend on the U.S, Russia and other dominant nuclear states to convert their spent fuel to MOX fuel, and then they would not be forced to develop indigenous separations capability to gain the domestic energy security they seek.

Suggestion 2—Nuclear Waste System Safety and Security: The U.S. Commercial Nuclear Industry should initiate an objective evaluation of the long term safety and security of a nuclear waste repository. They should evaluate three separate options:

> Direct disposal of spent fuel—can we really seal spent fuel in a repository with sufficient assurance that the plutonium will not be diverted for weapons use after the fission product activity has decayed to lower levels, in centuries to come? Also do we have confidence that the fission products will not leak to the biosphere prior to their decay?
>
> Separation of fission products, immobilization, and disposal in a geologic repository—How much does this reduce the risk of future theft and the risk of eventual leakage?
>
> Separation of fission products and transmutation to short-lived isotopes—How feasible is this over the long term and does it afford the basis for near term fuel cycle policy?

Whilst the Federal Government and Academia have evaluated these questions many times, it is time for a careful and thorough evaluation by the nuclear plant owners/operators themselves. They have the ultimate responsibility for the entire nuclear energy system, and therefore are in a good position to decide what's best in light of recent knowledge about the wastes and recycle. Establishment of new laws, regulations and licensing regimes should follow this initial determination by U.S. utilities of what course is best from a technical and safety point of view.

Suggestion 3—Establish a Dry Recycle Initiative in the U.S.: One possible common ground between the NP's and the RC's that should be seriously examined, and adopted if possible, is establishing a dry recycle regime in the U.S. which does not involve separation of plutonium from uranium or fission products, but still allows the recycle of spent fuel. This fuel cycle can use a proven (on a pilot scale) technology (known as AIROX or OREOX) originally developed in the U.S. in the 1960's but never commercialized.

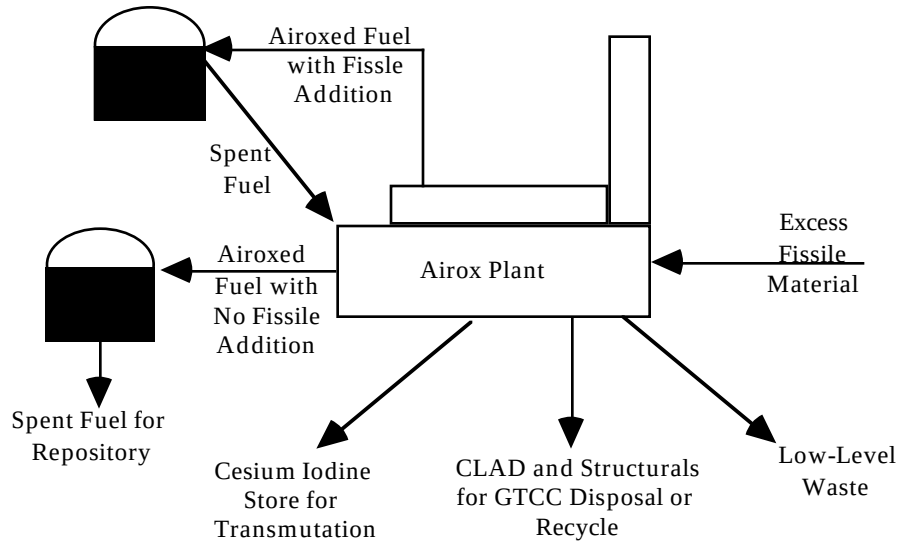
This fuel cycle approach would meet the basic goals of both RC's and NP's with only minimal compromise of their positions. It would not preclude continued use of the existing reprocessing facilities in the UK, France, and Japan, but would enable emerging nuclear nations such as South Korea, to achieve domestic energy security without separation of plutonium. In fact, it is through the initiative of the

South Korean and Canadian Nuclear establishments, with the active support of the U.S. State Department and Los Alamos scientists, that this dry recycle approach is emerging as a real technical possibility.

The Koreans call it DUPIC for DIRECT USE OF PWR SPENT FUEL IN CANDU'S. We propose to expand it to include recycle of spent fuel from LWR's back into LWR's as well as CANDU's. Such recycle requires the addition of excess fissile material, either plutonium, HEU, or when there is no longer an excess of weapons material, LEU, with enrichment of about 15% U235. The addition of fissile material will also permit multiple recycles of the oxide fuel, something that is not possible in the current DUPIC program.

A major study of this fuel cycle, as it could be applied in the U.S., was conducted by the Idaho National Engineering Lab assisted by Gamma Engineering in 1992 and reported to the Global 93 Conference.[6] That study concluded that this pilot scale technology could be demonstrated using existing LWR spent fuel, and using existing U.S. test facilities, and be ready for commercial deployment within 7 years, at a cost of $60 million. More recent work on the CANDU application is being reported by KAERI and AECL in other sessions at this conference.

The cycle is shown pictorially in the following:



By supporting the development of this fuel cycle for possible use within the U.S., both the NP's and the RC's would be opening the way for a new fuel cycle regime which is more environmentally sound than the direct disposal approach, and allows the productive use of excess fissile material derived from weapons at great monetary and environmental expense. And of greater importance, this fuel cycle can be used by non-weapons states needing a more secure peaceful nuclear future, without the proliferation hazards associated with plutonium separation. Such is the case in Korea today. If it were not for the availability of this more

safeguardable technology, the Republic of Korea would be forced to either proceed with a wet reprocessing program (either using new domestic facilities or existing facilities overseas) or in the absence of a site for spent fuel repository, slowdown their use of nuclear energy. Neither of these outcomes is in the U.S. or Korean national interest.

It is true that a definitive answer has not been developed regarding the economics of the DUPIC fuel cycle whether applied to recycle into CANDU's or into LWR's. Those currently involved in PUREX wet reprocessing will undoubtedly claim that DUPIC is more expensive, because of the need to fabricate new fuel remotely in hot cells. However, this may not turn out to be the case. In fact, because it does not depend on the use of wet chemicals, the DUPIC fuel cycle may actually turn out to be more economic than PUREX, at least while the world has large excesses of separated fissile materials. There are other dry recycle technologies that do not involve separation of fissile materials, including the pyrometallurgical system developed in the U.S. Actinide Burner Liquid Metal Reactor program. However, the DUPIC program has merit on its own right because it is the only technology which is based on existing proven water reactor technology, and therefore can be deployed in the near term. These other systems may have value for the long term, particularly in view of the high neutron economy of a fast reactor system but they do not solve the near term problem.

We believe that the only way to overcome the present impasse between the NP's and the RC's is to turn to a safeguardable recycle program that can be deployed in the near term, such as DUPIC or DUPIL. Such a course is a prerequisite, if the U.S. is to have a secure energy future domestically, and remain a player on the world non-proliferation scene.

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Part II

The Long Term Use of Nuclear Energy: An Evaluation Using Criteria for Proliferation Resistance and Socio-Ecologic Sustainability

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Abstract

If nuclear energy is to make a large-scale and long-term contribution to the future global energy supply, it has to be supplied in a way which is found to be generally acceptable to the public in informed, open and democratic societies. In order to achieve such acceptance, future nuclear energy systems have to prove to be able to fulfill stringent criteria for environmental and social sustainability as well as for proliferation resistance. Such criteria have been proposed and in this paper an evaluation is made of the challenges that these pose to the long-term use of nuclear energy.

Introduction

The nuclear community promotes a global long-term and large-scale use of nuclear energy in the future. If this vision of the future is to be realised, there are several difficult challenges that need to be addressed. These challenges involve supplying answers to growing environmental and non-proliferation concerns, as well as to questions of economic competitiveness.

There is a growing realisation that the global energy and resource use has to be environmentally sustainable in the long term. There has been a hope within the nuclear community, as yet not realised, that the threat of climate change due to global warming would stimulate a revitalisation of nuclear energy use.[1,2] It is, however, not sufficient to compare the environmental effects of the use of nuclear energy with those of burning fossil fuel. Fossil fuel use is not environmentally sustainable, has a limited resource base, and its use will be phased out in the future. There is a challenge for the nuclear community to convincingly show that the environmental effects of long-term and large-scale use of nuclear energy are comparable to those of the long-term large-scale use of renewable energy.

At the Extension Conference of the Non-Proliferation Treaty (NPT) in May 1995, international attention was once again directed to the possibility of using nuclear technology for both military and civil purposes. There is a challenge for the nuclear community to convincingly show that the military implications of long-term use of nuclear energy can be kept under control.

Despite attempts to show that the cost for nuclear electricity generation is low,[3] there are very few orders for new nuclear reactors. The few orders that are being made are from utilities in countries with strong central planning of the national energy systems. Meanwhile, there is a growing interest in the deregulation of energy supply systems. There is a challenge for the nuclear community to convincingly show that nuclear energy can economically compete in the long term on deregulated energy markets. Discussion of this issue is, however, beyond the scope of this paper.

The present global energy supply is based on the on fossil fuels (77%), renewable energy (18%) and nuclear energy (5%).[4] What will be the relative proportions between these three choices of energy supply in the future? Which factors determine the role nuclear energy will play? In this paper an analysis of these questions is made with the aim of giving plausible indications of what the answers to these questions could be.

Present and Future Global Energy Supply and Use

In order to be able to analyse the possibilities for the long-term use of nuclear energy it is important to understand which technologies will be relevant. We will therefore give a short background on the present status of and prospects for the three energy supply options; fossil, nuclear and renewable energy. We also need to carry out a short background discussion about what we mean by "the future", i.e., what time-scale is important to consider when discussing the long-term use of nuclear energy?

Fossil fuels meet over three quarters of present global energy supply, of which 26.5 % represents the burning of coal, 31 % oil and 19.5 % natural (fossil) gas. Of these, coal is the only fossil fuel likely to be available in substantial quantities beyond the middle of the next century.[4] The environmental impact on the global climate of carbon dioxide accumulation in the atmosphere may, however, strongly restrict fossil fuel burning well before the reserves are exhausted.[5]

The present global nuclear energy supply system is based on the energy from fission of the 0.7% uranium-235 in natural uranium that is fissile. The known natural uranium resources may last less than 100 years at current rates of consumption.[6] There are more speculative uranium resources that may be found to be usable, but if nuclear energy supply is to be rapidly expanded world-wide, perhaps as a respond to global warming concerns, it may not take long for the natural uranium resources to become scarce.[7-9] In order to multiply the recoverable nuclear energy from mined resources one may have to commence to breed fissile material from more abundant nuclides. The two most commonly considered fertile materials are uranium-238 that can be converted into plutonium-239, and thorium-232 that can be converted into uranium-233. In both cases this is done in special breeder reactor fuel cycles. Of these, the fast plutonium breeder reactor fuel cycle is the most developed, as it fits closely into the present military and civil nuclear fuel cycles.

The use of fast plutonium breeder reactors and reprocessing plants, the "plutonium (energy) economy", would increase the energy supply that is available from natural uranium resources by a factor of over sixty. **The commercialisation of breeder nuclear fuel cycles seems essential in the long term if nuclear power is to make more than a minor contribution to global energy supplies**. When exactly that time comes is dependent on how large the speculative uranium resources finally turn out to be.

The potential for using renewable energy sources is very large. The incoming radiation from the Sun to the Earth is on the order of 172,500 TW, or about 13,500 times the global energy use. How much of this energy can be harvested? Today, hydroelectric energy accounts for 7%, traditional biomass for 14% and "new" biomass for 2 % of global energy supply. The potential for large-scale supply of hydroelectric energy, geothermal energy and tides is limited, while the prospects for large-scale supply of wind energy, solar electricity and heating and biomass energy is larger.[10] However, land use constraints for feeding and providing materials for a growing world population will limit biomass energy supply.[11] **In order to use renewable energy on a large scale in the long term, there appears to be a need for the commercialisation of solar electricity**. Solar electricity has a much higher solar energy conversion efficiency per unit area than biomass energy supply and can advantageously be used in non-bioproductive areas. Recoverable solar energy is an estimated 80 times the present global energy use,[12] but the commercialisation of large-scale generation of solar electricity using photovoltaics is just commencing.

Energy futures are not only a question of supply. Equally important is how much energy is used. However, energy use as such has no value. What we want are the services that we get from using energy. If we can drive a car the same distance for one quarter the amount of fuel that we previously have used, we get the same service for less. In a future global energy system where energy supply will be more costly, energy use will be highly efficient and may not necessarily be more costly per unit service compared with today's. Efficiency is already being strongly promoted as a way to delay climate change from fossil fuel burning.[13]

How much energy will be used in the future? Attempts to predict the future supply and use of energy are often carried out by creating scenarios. There are two main types of scenarios, projections and normative scenarios. **Projections** are calculations based on a macro-economic model of the present energy system where certain assumptions are made of future changes in different variables. Projections are also called top-down scenarios and often include a "business-a-usual" case as well as a high and a low case. Projections of future energy supply are continually being made and updated.[4,14] Projections beyond a time of 15-25 years into the future are commonly considered less meaningful.

A different type of scenario of the future are **normative scenarios** or bottom-up scenarios. In such scenarios certain assumptions are made of how energy is supplied and used in the future and the scenario is then built up around these

assumptions. Normative scenarios are designed to identify the opportunities presented by a changeable world and allow the time-scale of the scenario to be moved further into the future. In later years a number of long-term normative scenarios for future energy supply and use have been presented.[8,15-19] Long-term scenarios have an intrinsic high level of uncertainty. On the other hand this has historically also been found to be true for projections of future energy supply and use.[20]

The total global primary energy use is today over 400 EJ (111,000 TWh) per year and is rising. Scenarios for global long-term energy use depend on the choice of levels of population growth, levels of implementation of energy efficiency potentials, levels of choice of energy service and levels of global equity. A scenario with full global equity, i.e., all the Earth's inhabitants are allowed to use the same amount of resources, with service levels available in the developed world today, with modest implementation of efficiency potentials and with a global population stabilised at 10 billion people, gives a future primary energy use of approximately 1,000 EJ per year, i.e., two-and-a-half times that of today. Improved control of population growth, radical application of new technology and organisation to improve the efficiency of energy use, and modestly reduced use of services could lower this figure even further.

In this background discussion we have found that there are a number of options for long-term energy supply and a number of scenarios for future energy use. On the supply side, fossil energy has constraints in the resource base and causes detrimental environmental effects, and its use will very likely highly restricted within 50 to 100 years. It is in this perspective long-term energy supply options should be discussed. **Thus, when we discuss long-term energy futures, we are discussing a time-scale starting from the second half of the next century and then onwards "forever."** On this time-scale nuclear energy probably has to rely on breeder reactor systems and renewable energy probably has to rely on solar electricity generation, if they are to be able to provide a substantial part of the global energy supply. This perspective is difficult to grasp and it provokes comments about how difficult such a transition may be. One should, however, keep in mind that in a period of 100 years the whole global energy supply system will be completely replaced at least two times.

We have thus an idea of what technologies we should keep in mind and which time-frames are involved when discussing long-term energy futures. Let us carry out a short discussion of public acceptance of nuclear energy before looking at criteria for long-term nuclear energy use.

Public Acceptance of Long-Term Use of Nuclear Energy

If large-scale use of nuclear energy is to be an important energy supply in the future it has to obtain what is commonly called public acceptance. Even though nuclear energy has found public acceptance in some countries, the technology has

not been successfully accepted in others. In addition, continual efforts have to be made to keep the public acceptance at high enough levels even when some acceptance has been found.[21] However, if nuclear energy is to be a successful competitor for large-scale energy supply in the future, there has to be a global acceptance of future nuclear fuel cycles and technology by the public in informed, open and democratic societies. It is important to remember that the main energy supply competitor in the long run will be renewable energy sources. These may have an easier task in obtaining public acceptance.

What are the main points vital to obtaining public acceptance for nuclear technology in the future? Firstly, the direct environmental impact of long-term use of nuclear energy has to be very small. There is absolutely no room for accidental releases of radioactivity and the routine releases have to be extremely low. Secondly, the use of nuclear energy in the future should not cause problematic security considerations, either within the society or between nations. This means that nuclear weapon proliferation threats from civil nuclear energy use have to be kept to a minimum. Thirdly, there should be a concern for inter-generational equity. Burdens on future generations should be avoided. This has consequences when discussing the long-term waste problematique arising from the use of nuclear energy. Fourth, the energy system has to be reliable. Fifth, the energy system has to be able to be used in a non-discriminatory way. In the long term there has to be global equity of resource use and any future energy supply source should allow for this. Finally, there is a need to address public concerns for the democratic control over energy supply and about which complexity and scale energy supply systems should have.

The economics of energy supply has not been mentioned above. There is an assumption that energy supply has to be cheap in order to be accepted. While there is no reason to doubt that economics will play an important role also when choosing energy systems in the future, the factors mentioned above will in the long run probably be more important. A sign of this is the attempt to internalise external costs when comparing the economics of energy supply systems.[22] With the increasing global acceptance of the concepts of sustainable resource use and sustainable societies, ethical and environmental considerations are being found increasingly more important compared to economical considerations.

In the next sections we will first analyse how future nuclear power supply has to respond to criteria for sustainable use of resources. Secondly, we will examine the challenges that criteria for proliferation resistance provide for long-term use of nuclear energy.

Meeting Criteria for Socio-Ecologic Sustainability

Since the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro in 1992, **the notion that long-term energy supply has to be sustainable is gaining wider and wider acceptance**. The term sustainability was

brought to the global focus in 1987 in the report of the World Commission on Environment and Development (WCED), often called the Brundtland Commission.[23] Sustainability is defined in the report as being able to meet the needs of the present generation without compromising the ability of future generations to meet their own needs.

Since this "definition" was put on paper, the question of what sustainability and sustainable development is has been discussed at great length. Also the nuclear community has made attempts to interpret the term "sustainable development."[24] While the discussion about definitions has at times been confusing, there is a growing clarity about the criteria a sustainable society has to comply with. The following socio-ecological principles for a sustainable society have been developed at the author's home institute and we will use them in the analysis below[25]:

1. Substances extracted from the lithosphere must not systematically accumulate in the ecosphere.
2. Society-produced substances must not systematically accumulate in the ecosphere.
3. The physical conditions for production and diversity within the ecosphere must not be systematically deteriorated.
4. The use of resources must be effective and just with respect to meeting human needs.

Let us examine the implications these criteria have for the future use of nuclear energy.

Principles 1 and 2 describe the limitations for accumulation of foreign substances in nature. They state that the amount of material (mined or man-made) that man disperses in his surroundings cannot over time exceed the amount that is naturally sedimented or broken down into commonly naturally existing constituents.

The lithosphere is the crust of the earth, and when uranium or thorium ores are mined material is extracted from the lithosphere. The ecosphere is what lies above the crust, i.e., the soil, the living organisms, the atmosphere and the hydrosphere. This means that principle 1 restricts the release of mined materials in nature. It is important to realise that this means not only the materials that are originally sought after when mining, but also the large amounts of residues and sludge that are a result of the mining and processing of the ores. Uranium mining at present has, justly or not, a bad reputation when it comes to releases of large volumes of waste into the environment.

In a long-term breeder reactor system, whether based on the uranium/plutonium or thorium/uranium use, the mining problems should not be a problem as very little new material will be mined. However, unless uranium and

thorium mining already today are made sustainable with regard to release of waste it may be difficult to persuade a hesitant public of the value of nuclear energy. Costs for restoration of already contaminated areas and closed mines may thus have to be taken today. In addition, there are and will always be some losses of uranium in enrichment, fuel fabrication and reprocessing plants that may end up in the environment.

Principle 2 is probably the principle that offers the largest challenges to a long-term nuclear future option. The principle discusses the management of substances produced by the society. Most nuclides produced in a nuclear reactor qualify as such substances. This means that the systematic release of radionuclides must be prevented, both as routine releases during fuel fabrication, reactor operation and reprocessing and in accidents. Today, routine releases are largest at reprocessing plants, and new designs for closed-process reprocessing plants may be necessary.

The prevention of routine releases can probably be managed, although it may involve some cost. The long-term release in accidents may be a bigger problem. The development of safer reactor systems is a necessity, not only for conventional reactors, but also for the breeder reactors that are needed in the long run. The long-term nuclear energy option can probably not afford another large-scale accident and still remain a viable option in the eyes of the public. Efforts are underway to develop new safer reactor systems, but it remains to be seen if these are successful, especially when it comes to breeder reactor systems.[26,27]

If nuclear power is to take a large-scale role in future energy supply one has to appreciate that we are discussing a nuclear capacity of over 20 000 GW_e to supply 50% of a global primary energy supply of 1 000 EJ with an availability of 80%. This is over 20 times today's nuclear energy capacity and represents almost 15 000 reactors with a capacity of 1.3 GW_e. These may all be breeder reactors if a breeder energy economy is realised, relying on the uranium/plutonium or the thorium/uranium fuel cycle. Presently more than 7 000 reactor-years of operation have been achieved,[28] but in the above scenario this would be less than half the yearly number of accumulated reactor-years. According to Rasmussen the median core melt probability of today's fleet of reactors is $5 \cdot 10^{-5}$ per reactor-year.[26] Even if a safety standard five times higher was used in the scenario above there would be a core melt frequency of 0.75 per year, i.e., there would be a probability that one serious accident would happen every seven years, "forever." This would clearly be unacceptable, and it is difficult to see what probability for serious accidents that would be acceptable. Each accident that occurs will decrease the inhabitable or cultivable land area and in the long run this could mean that a considerable land area will not be suitable for societal use. This is an issue needs much further discussion and evaluation in the future.

Principle 2 also holds relevance for the discussion of how to handle nuclear waste. If one can consider long-term geologic disposal of waste, nuclear or non-nuclear, as a "man-made sedimentation process," such disposal would comply with

principle 2. Such an interpretation seems reasonable, especially considering that there will very likely be a need for final disposal of other now commonly used materials that are currently being phased out of societal use, such as mercury, cadmium or even lead.

Principle 3 covers the ability of the ecosphere to supply food, materials and energy to the society in the long term. The intent is here to include human activities that threatens the ecosphere and biological diversity, such as non-sustainable agriculture or forestry. The relevance for nuclear energy supply systems could possibly be when large accidents make larger areas of land non-bioproductive.

Principle 4 describes the distribution and effectiveness of resource use. In the long run it is implausible to think of a stable global world order that is not equitable in resource use. In such a society it is clear that any long-term energy supply that is to have a global impact will have to be usable without discrimination. It will be very difficult to forbid nuclear power generation facilities in areas of the world that show social unrest. On the other hand, if we are discussing an equitable world, the risks for such unrest may be much less than today. Justice can also be inter-generational, i.e., resource use should not put a burden on future generations. It is essential that plans for long-term use of nuclear energy show that the long-lived nuclear wastes produced can be destroyed or disposed of in a way that gives no long-term environmental or security problems.

Meeting Criteria for Proliferation Resistance

The long-term goal for nuclear weapon disarmament is a nuclear-weapon-free world.[29] This was once again clearly established at the conclusion of Extension Conference of the Non-Proliferation Treaty (NPT) in May, 1995. The NPT was at this meeting made permanent while "reiterating the ultimate goals of complete elimination of nuclear weapons and a treaty on general and complete disarmament under strict and effective international control."[30] In such a world system there will be a need for a strong control of any use of civil nuclear technology. It is thus important that any system for long-term use of nuclear energy takes into account the need to be as proliferation-resistant as possible.

We have earlier established that long-term and large-scale nuclear energy supply may need to rely on breeder reactor use, either using the uranium/plutonium or the thorium/uranium fuel cycles. In the previous sections we have not in detail discussed different reactor options and we will not do so in this section either. However, a point has to be made concerning the proliferation problems of the presently most developed breeder reactor system, the fast plutonium breeder reactor. All forms of plutonium should be regarded with equally serious concern when it comes to risks for nuclear weapons proliferation.[31,32] However, in the long run fast plutonium breeder reactors will use plutonium of so called weapons-grade quality as the "energy carrier". As an example, a Superphenix-type radial blanket irradiated for 39 months of full power contains 96.7% Pu-239, 3.2% Pu-240 and 0.1%

Pu-241.[33] There are thus difficult proliferation risks to be managed in a long-term plutonium energy economy, an issue that has to be faced openly. There are other breeder options for long-term nuclear energy use that may have advantages when comparing proliferation-resistance.[34-36]

The following criteria for proliferation resistance that a future long-term nuclear energy supply system should satisfy have been proposed[37]:

i) Restrictions on sensitive nuclear technologies and materials shall be non-discriminatory among nations.

ii) Fissionable weapons-usable material that is not contained in spent fuel and facilities to enrich uranium or to separate plutonium shall not exist outside international centres.

iii) As far as possible, fissionable weapons-usable material that is not contained in spent fuel shall not be produced even at the international centres.

iv) Spent fuel shall be stored and disposed of in international centres.

v) Reactors under national authority shall be designed to reduce to very low levels the production of weapons-usable material in spent fuel (on the order of a critical mass or less per year of gigawatt of capacity).

If we look at the criteria we see that the concepts **non-discriminatory, internationalisation and very low production of fissile material in national reactors** are three key ingredients for an "acceptable" proliferation-resistant nuclear fuel cycle. These concepts should be kept in mind when proposing long-term solutions for nuclear energy use. Internationalisation of the nuclear fuel cycle appears to be an attractive way to move forward, but large political efforts and institutional changes are required if this path is to be successfully followed.[38]

Concluding Remarks

It may appear to be a largely academic effort to discuss energy supply in a future that is more than half a century away. Indeed this may be true if detailed scenarios for future energy supply were proposed. This is not done here. There are many options, both non-nuclear and nuclear. On the nuclear side we have not even mentioned accelerator-based systems, fission-fusion hybrid reactors or fusion energy above. What is discussed in this paper are the trends that can be seen in how the public views environmental and non-proliferation issues. There are evident signs that environmental sustainability will play an increasingly important role for public acceptance of future technologies. Likewise, it is likely that the public will pay increasing attention to the security implications of the use of future technologies.

There are tendencies within the nuclear community to de-emphasise these trends and to regard the problems of attaining public acceptance for nuclear energy as an information problem.[24] However, in order to obtain acceptability for a long-term large-scale breeder reactor and reprocessing nuclear fuel cycle the challenge of these issues have to be addressed seriously.

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Design Considerations for a Pyroprocess Recycle Facility

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Abstract

The conceptual design of future commercial fuel cycle facilities for the support of the Advanced Liquid Metal Reactor (ALMR) are described. The design of these facilities were developed during the past five years by an industrial team coordinated by the General Electric Company (GE) under contract with United States Department of Energy. Facility design and cost estimates were prepared by Burns and Roe Company. The design of pyrochemical process systems and equipment was based on a development program performed at Argonne National Laboratory (ANL). While additional process development is needed to complete this program, sufficient progress has been made to provide a suitable basis for the conceptual design of future commercial fuel recycle facilities.

Introduction

The current ALMR design has evolved into a highly cost effective 1866 MWe power plant consisting of six 840 MWt reactors arranged in power blocks. Two reactors in each power block work together to drive a 622 MWe turbine. The ALMR is based on the design of the Power Reactor Inherently Safe Module (PRISM)[1] which was initiated by GE in 1982. The current plant is designed with a burner core to consume plutonium and minor actinides (fissile material) from Light Water Reactor (LWR) spent fuel. The fissile material is removed from the LWR spent fuel and fabricated into new ALMR fuel assemblies in a Spent Fuel Recycle Facility (SFRF). This facility also recycles the ALMR spent fuel and processes the waste to a form that is suitable for the repository. This overall system has been identified as the ALMR/Actinide Recycle System.[2]

Evolution

Design and cost estimates of central fuel recycle facilities were developed from 1990 to 1993 to support the operation of ALMRs with breakeven cores (no net supply of fissile material after startup, no net production of plutonium). A LWR Spent Fuel Process Facility (LWR SFPF) was designed to convert the LWR spent fuel into startup cores and first reloads of metal fuel for the ALMR. This facility was sized to

support the startup of two-thirds of an ALMR power plant each year (1200 MWe). A Central Fuel Recycle Facility (CFRF) was designed to receive the spent metal fuel from eight ALMR power plants, and process this fuel into replacement fuel assemblies for shipment back to the ALMR sites. Both facilities processed the high level waste into a stable form for loading into metal containers. These containers were stored in an air cooled facility on the site until the decay heat had decreased adequately for shipment to the repository. Each of these central facilities was designed as a separate plant to be located on its own site for commercial operation.

Fuel handling and storage facilities at each ALMR power plant site were provided by a separate Fuel Service Facility (FSF). This facility received spent fuel from each reactor on the site, provided storage as needed and loaded the fuel into casks for shipment to the CFCF for recycle. The FSF also provided similar functions for the new fuel required by the ALMR power plants.

The use of a Collocated Fuel Recycle Facility (CLFRF) at each ALMR power plant site in lieu of the CFRF to recycle the ALMR spent fuel was also evaluated. The purpose was to eliminate offsite transportation of ALMR fuel to reduce proliferation risks. The functions of the FSF were integrated with the CLFRF. The costs associated with this system were higher than the costs for the CFRF due to the economy of scale. The throughput of LWR spent fuel and the ALMR fuel in these systems are shown in Table 1.

During 1994 the design of the ALMR core was changed from the breakeven core to a burner core (continuous supply of fissile material, consumes plutonium) to be more effective in the utilization of the fissile material in the LWR spent fuel. After the fabrication of the initial cores and first reload cores, this approach requires that the fissile material from the LWR spent fuel be blended with the recycled ALMR fuel throughout the life of the plant. This resulted in the development of the SFRF which is collocated at each ALMR power plant site and replaces the central

Table 1. Pyroprocess Facility Capacities for Breakeven Core.

Facility Type (ALMR Plants Served)	Input		Output	
	MTHM/yr	Type	MTHM/yr	Type
LWR SFRF (Startup 1200 MWe ALMR/yr)	1763	LWR Spent Fuel	146	ALMR New Fuel
CFRF (8 ALMRs)	155	ALMR Spent Fuel	174	ALMR New Fuel
CLFRF (1 ALMR)	19.4	ALMR Spent Fuel	21.7	ALMR New Fuel

facilities (LWR SFPF and CFRF). This eliminates all transportation of fissile material off site after the receipt of the LWR spent fuel and improves the overall proliferation resistance of the ALMR.

The SFRF is a commercial fuel recycle facility that provides for the processing of the LWR spent fuel, recycling the ALMR spent fuel, fabricating initial cores for plant startup fuel and initial reloads as well as fabricating replacement fuel assemblies during the 60 year life of the plant. High level radioactive waste from processing the LWR spent fuel and recycling ALMR spent fuel is conditioned within the facility and placed into a highly concentrated, leach-resistant form suitable for disposal in a waste repository. In order to reduce the volume of space needed in the repository, concentrated waste is initially placed in small containers that have decay heat values higher than could be accepted at a repository. Water cooled storage is provided for 10 years to allow cooling of the waste to acceptable levels. These small containers are then packaged into large containers for shipment to the repository. The SFRF also incorporates all the features of the Fuel Service Facility to support the refueling of the ALMR power plants on the site. The ALMR spent fuel is stored in an air cooled vault in the SFRF.

Process

The SFRF utilizes an electrometallurgical process (pyroprocess) that has been under development at ANL for more than 10 years for recycling metal fuel used in the ALMR.[3] During the past 5 years this process has been adapted for removing the plutonium and minor actinides from the LWR spent fuel. The LWR spent oxide fuel is converted into ALMR metal fuel. The main features and functions of the pyroprocess system used in the SFRF are shown in Figure 1.

The spent fuel from LWRs and ALMRs is disassembled and chopped by the use of remotely operated equipment. The chopped fuel is then transferred to a cell where different equipment is used to process either the LWR or ALMR spent fuel to produce metal fuel for purification in the cathode processor. For processing the LWR spent fuel, the chopped pieces are placed in a reduction vessel where a salt

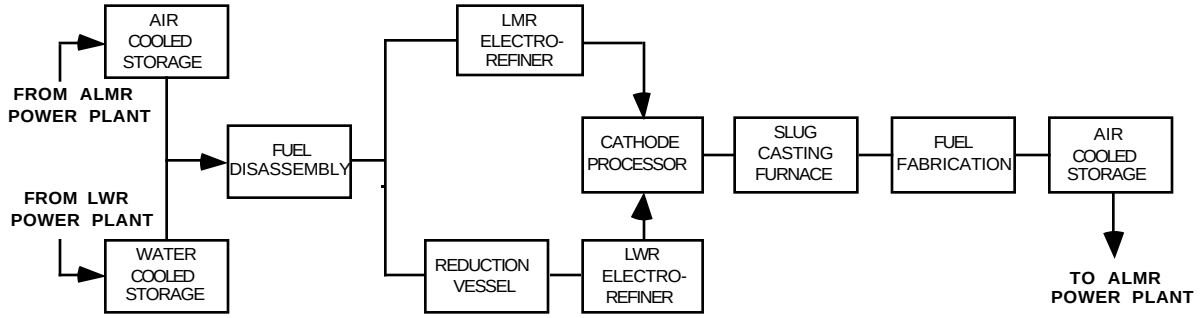


Figure 1. SFRF Functional Diagram.

process is used to reduce the oxide fuel to metallic salts containing plutonium, minor actinides, uranium and non-gaseous fission products. The oxygen and fission products are removed by recycling the salt through a cleanup system. The metal fuel particulate material is placed onto anodes in the LWR electrorefiner. Electrochemical separation of the uranium from the transuranic material (TRU which contains plutonium and minor actinides) occurs in a high temperature salt bath within the LWR electrorefiner. Most of the uranium is collected on one cathode and the TRU plus some uranium is collected on another cathode. The uranium and TRU contained on the cathodes from either the LWR or LMR electrorefiners are processed separately in a high temperature cathode processor to purify the material and produce ingots. A metal fuel alloy is created by combining the TRU and uranium ingots in a crucible with other materials added as required. The crucible is heated in a slug casting furnace to produce metal fuel slugs. These slugs are transferred to an assembly cell where they are placed into fuel rods and assembled into new ALMR fuel assemblies.

For processing the ALMR spent fuel, the chopped pieces of metal fuel are transferred from the disassembly area to the processing area where they are placed into anode baskets. The baskets are placed into the LMR electrorefiner. These units operate in a similar manner as the LWR electrorefiners, using a different salt bath. The non-gaseous fission products are removed by recycling the salt through a separate cleanup system.

Beyond the electrorefiners, common equipment is used to complete the processing and fabrication of new ALMR fuel from both LWR and ALMR spent fuel sources. This equipment includes the cathode processors, slug casting furnaces and the various components which are required for fuel assembly fabrication.

The SFRF will be operated in three phases. During the startup phase (2 years), initial cores will be fabricated for the 6 reactors in the ALMR power plant. Fuel reloads (partial cores) will be fabricated during the transition phase (3 years). All of these cores will use the fissile materials from LWR spent fuel. During equilibrium operation (55 years), ALMR fuel will be fabricated from a blend of fissile material from the LWR spent fuel and the recycled ALMR fuel. The fuel throughputs during these phases are shown in Table 2.

The capacity of each item of process equipment and the size of each item was determined by ANL. The number of items needed to support the plant throughput for each phase of operation was established based on process flow sheets provided by ANL, as shown in Table 3. The installed spare equipment items are also included.

Table 2. Pyroprocess Facility Capacities for a Burner Core.

	Input		Output	
Phase	**MTHM/yr**	**Type**	**MTHM/yr**	**Type**
Startup	915	LWR Spent Fuel	44	ALMR New Fuel
Transition	317	LWR Spent Fuel	15	ALMR New Fuel
Equilibrium	48	LWR Spent Fuel	16	ALMR New Fuel
	15	ALMR Spent Fuel		

Table 3. SFRF pyroprocess equipment.

	Number of Components		
Equipment	**Startup**	**Transition**	**Equilibrium**
Reduction Vessel	5	3	3
Electrorefiner (LWR Fuel)	7	4	3
Electrorefiner (LMR Fuel)	0	0	3
Cathode Processor	3	3	3
Slug Casting Furnace	2	2	2

Some of the LWR process equipment that becomes idle after the production of the startup fuel will be decontaminated and shipped to the next SFRF while other LWR processing equipment will be converted for LMR fuel recycle functions during the equilibrium phase. The extra space that becomes available within the process cell after the startup phase will be used to support maintenance and provide surge capacity for storing waste.

Material Balances

Boiling Water Reactor and Pressurized Water Reactor spent fuel provides the LWR feed material required for the ALMR plant. Material balances were prepared to determine the material flows during the three phases required for processing LWR and ALMR spent fuel. These balances were based on ANL process flowsheets. The material balances were used to determine the amount of feed material required and the waste that would be generated to provide a basis for sizing the processing and storage areas as well as determining the heat removal requirements. This information was used to design the main process cell, the waste process cell, the air cooled storage area for the ALMR fuel and the water cooled storage area for the LWR spent fuel and the mineral waste.

Facility Design

The layout of the first and second floor of the SFRF is shown in Figures 2 and 3. The cost effectiveness of the SFRF is achieved by sharing many functions. At the head end of the facility, the LWR spent fuel assemblies and the ALMR spent fuel assemblies are disassembled and chopped into small pieces in a common Fuel Disassembly Cell using adapters for the equipment and fuel handling. One Process Cell is used for the equipment needed to process the chopped LWR and ALMR spent fuel. This includes the reduction vessels and electrorefiners required for the LWR spent fuel processing, the electrorefiners required for the ALMR fuel, and common cathode processors and slug casting furnaces for making fuel slugs. layout of the process cell is shown in Figure 4. The equipment was arranged within the process cell based on time and motion studies related to material handling, operation and maintenance. Overhead cranes, manipulators, transfer carts, viewing windows and other equipment as well as space for access and lay down is provided to support remote operation and maintenance. Redundant equipment is provided to assure plant production requirements can be met.

A separate Fuel Fabrication Cell is used to fabricate all ALMR fuel assemblies. A common Waste Processing Cell provides for one salt recovery and waste processing system associated with the LWR spent fuel processing and another salt recovery and waste processing system associated the recycle of the ALMR spent fuel. Waste concentration and packaging is performed in this cell to produce a low volume, leach resistant, high level waste form containing the fission products and other waste material. This reduces the cost and environmental concerns associated with the burial of high level waste. Metal waste from the LWR and ALMR spent fuel (end fittings, cladding and hardware) is reduced in volume with a melter which also provides for waste decontamination. Some of this metal waste would not be high level waste and can be buried at low cost or possibly reused in the future.

The incoming LWR spent fuel is stored in a water cooled pool. Since a much larger quantity of LWR fuel is received during the startup period than is received for the remainder of the plant life, space becomes available that is then used for the 10 year storage of the high level waste prior to shipment.

Large quantities of low enriched uranium are produced during the processing of LWR spent fuel. About 2750 MT of uranium are produced during the first five years of SFRF operation and 48 MT/year are produced during the remaining 55 years of plant life. This uranium is purified in a cathode processor to minimize the contaminants for shipment off site for reuse in the fabrication of new fuel for the LWRs. This eliminates the need to mine an equivalent amount of natural uranium, thereby reducing the fuel costs for the LWRs and maintaining stable uranium prices for the future.

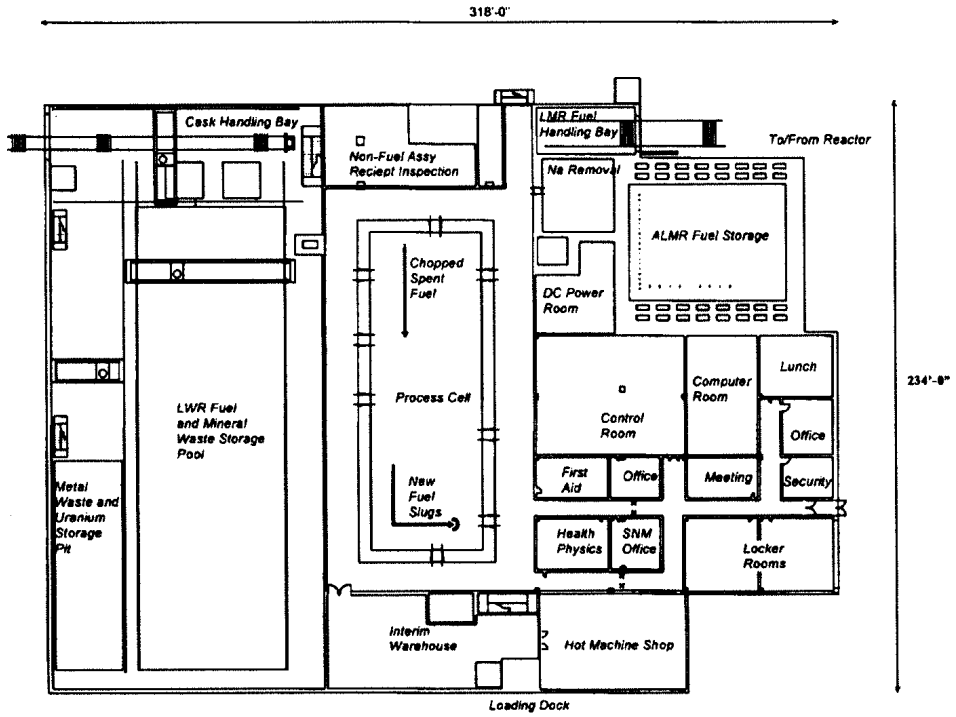


Figure 2. SFRF layout—first floor.

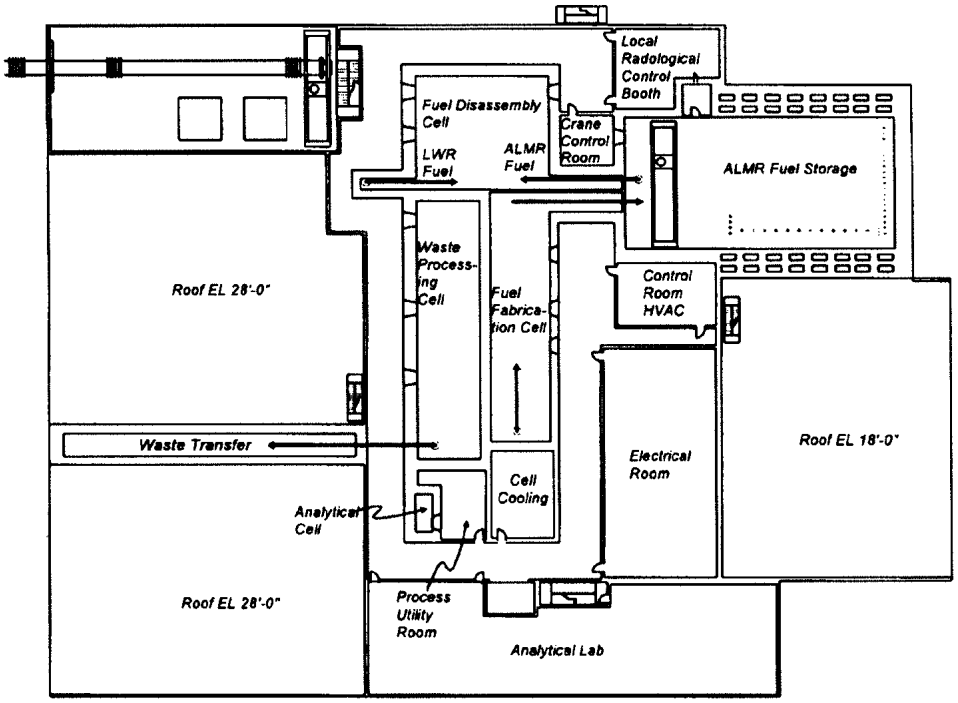
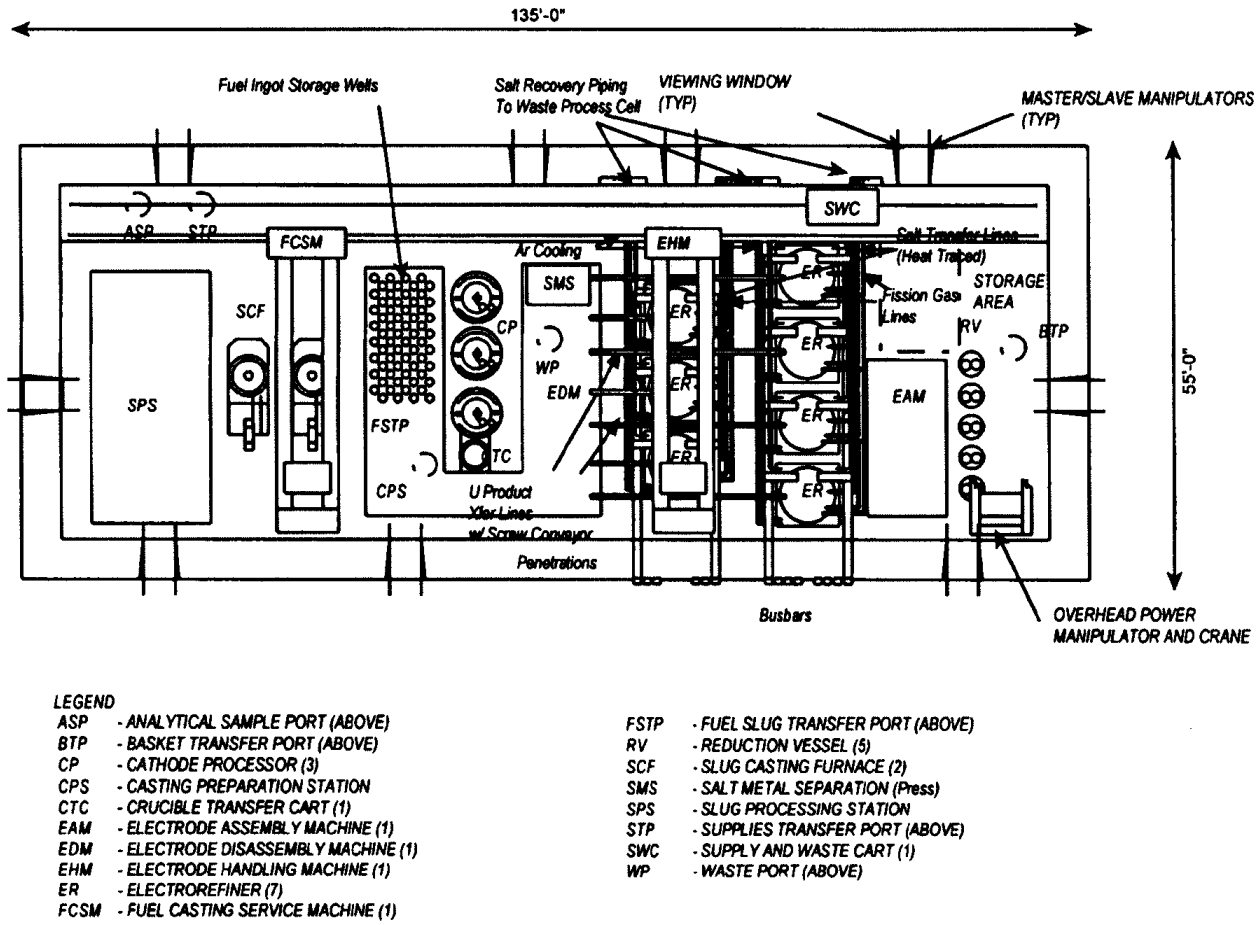


Figure 3. SFRF layout—second floor.



LEGEND

ASP	- ANALYTICAL SAMPLE PORT (ABOVE)
BTP	- BASKET TRANSFER PORT (ABOVE)
CP	- CATHODE PROCESSOR (3)
CPS	- CASTING PREPARATION STATION
CTC	- CRUCIBLE TRANSFER CART (1)
EAM	- ELECTRODE ASSEMBLY MACHINE (1)
EDM	- ELECTRODE DISASSEMBLY MACHINE (1)
EHM	- ELECTRODE HANDLING MACHINE (1)
ER	- ELECTROREFINER (7)
FCSM	- FUEL CASTING SERVICE MACHINE (1)
FSTP	- FUEL SLUG TRANSFER PORT (ABOVE)
RV	- REDUCTION VESSEL (5)
SCF	- SLUG CASTING FURNACE (2)
SMS	- SALT METAL SEPARATION (Press)
SPS	- SLUG PROCESSING STATION
STP	- SUPPLIES TRANSFER PORT (ABOVE)
SWC	- SUPPLY AND WASTE CART (1)
WP	- WASTE PORT (ABOVE)

Figure 4. Process cell equipment arrangement.

An air cooled storage vault provides space for the storage of the ALMR spent fuel assemblies for the burner core based on an 18 month refueling cycle. Space is also provided for the handling and storage of the non-fuel core assemblies. New ALMR fuel is stored until ready for return to the power plants.

Common facilities within the SFRF provide for cell atmosphere cooling and inerting systems, offgas collection systems, building ventilation systems, remote and contact maintenance facilities, a control room, electrical supplies, personnel control areas, change rooms and analytical laboratories. Some of these facilities are provided on the third floor of the SFRF. Since this facility is intended to be operated commercially by an organization separate from the utility company operating the power plant, an administration building and warehouse is provided for the SFRF. This permits startup and operation of the SFRF prior to the ALMR power plant startup so that the fuel can be fabricated for initial reactor loadings.

The SFRF reflects commercial practices for the design of fuel recycle and fuel fabrication facilities. Remotely operated cells are provided for fuel disassembly, fuel

processing, fuel fabrication, waste processing and waste packaging. Process equipment is designed for remote operation and maintenance. Contamination control is provided by air locks, atmosphere pressure control, and layout to provide for flow paths for personnel and equipment.

The SFRF is designed to provide for proliferation and diversion resistance. Features that support this are the inability of this pyroprocess to separate the plutonium from the minor actinides. This mixture is not suitable for weapons. The simple systems and small components along with batch operation provides for excellent accountability of the special nuclear material. The location of high temperature, highly radioactive process systems within inert, shielded cells minimizes personnel access providing for a high degree of proliferation resistance. The ability to process the LWR and ALMR spent fuel and fabricate new ALMR fuel in one compact facility and avoid off site transportation of the new and spent ALMR fuel reduces the opportunity for material diversion.

Summary

The SFRF is designed to provide all the fuel cycle services required to support the operation of one 1866 MWe ALMR power plant. The SFRF provides for the processing of the LWR spent fuel required for the startup cores, reload cores and replacement fuel for the life of the power plant. It also provides for the recycling of the ALMR spent fuel, the fabrication of ALMR new fuel, the processing of all waste streams, the packaging of wastes, and the interim storage of waste prior to shipment to a waste repository or other disposal area. Facilities are available for the storage of all incoming LWR spent fuel, all ALMR spent fuel and all ALMR new fuel to support reactor refueling.

All of these functions are combined within a single facility which is collocated on the same site as the ALMR power plant. Sharing many functions within the facilities reduces capital and operating costs. The design also reduces risk of diversion and proliferation of Special Nuclear Material (SNM). Collocation of this facility eliminates the need for off site transportation of SNM following the receipt of LWR spent fuel from either interim storage or the utility fuel pools.

The fuel cycle services provided by the SFRF to support one ALMR power plant resulted in a fuel cycle busbar cost of about 12 mils/kWh. The total busbar cost of the ALMR (including the fuel cycle busbar cost) is about 40 mils/kWh. This is competitive with the advanced LWR total busbar costs based on the current once-through uranium fuel cycle and direct disposal of the spent fuel. Deployment of advanced LWRs and ALMR/Actinide Recycle Systems during the next century can provide an economical solution to the disposition of LWR spent fuel by the efficient utilization of plutonium and minor actinides to produce electricity and simplifying the waste form to reduce repository costs.

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System Considerations for Actinide Recycle in Fast Reactors

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Abstract

The benefits that can be achieved by completing the development of the Advanced Liquid Metal Reactor (ALMR) and the electrometallurgical recycle system (Actinide Recycle System) can far exceed the cost of the remaining development program. Use of the ALMR/Actinide Recycle System to close the back end of the fuel cycle provides for lower costs to the Government (taxpayers), the electric power industries, and the rate payers. These cost benefits and other advantages to the U.S. nuclear program are discussed.

Introduction

Problems encountered with the U.S. Yucca Mountain repository program have resulted in the need to delay the date when spent fuel could be received for direct disposal from 1998 to 2010. Further delays and significant cost increases have been forecast by several organizations.

The U.S. Government now plans to meet its obligation to accept spent nuclear fuel from commercial LWRs in 1998 by providing multipurpose canisters for the shipment and storage of the spent fuel at a central interim storage facility. Site work and analysis of the deep, geologic repository at Yucca Mountain will continue at a reduced level of effort. This provides the time required to reevaluate the use of fuel recycling instead of direct disposal.

Most other nations with sizable commercial nuclear power programs are in the process of or are planning to recycle the spent fuel that is being discharged from their Light Water Reactors (LWRs) in order to conserve energy resources and to condition the waste for disposal. With this approach, the economic and environmental advantages of nuclear power will remain available through the 21st century and beyond and the environmental risks associated with direct disposal of spent fuel will be reduced by conditioning the waste prior to disposal. Over the past 10 years the U.S. Government has funded an ALMR design team lead by the General Electric Company (GE) and a fuel cycle development team lead by Argonne National Laboratory (ANL).[1] These teams have made substantial progress in developing a competitive ALMR and a fuel cycle based on the electrometallurgical process

(Actinide Recycle System) that can process LWR spent fuel and LMR spent fuel in a low cost, diversion resistant system. Recent studies show that LWR spent fuel can be processed at no cost versus the many hundreds of dollars per Kg required to reprocess in an aqueous reprocessing plant. The ALMR/Actinide Recycle System is configured with a burner core which utilizes the plutonium and minor actinides removed from the LWR spent fuel to produce electricity. Deployment of this system early in the next century provides economical closure of the backend of the LWR fuel cycle and supports the continued use of LWRs.

An additional advantage of the Actinide/Recycle System is that the waste is conditioned prior to disposal by converting it to a highly leach resistant form whose radiological toxicity will decay to the level of natural uranium in less than 300 years, a process that would otherwise take 10,000 years to accomplish.

It is time for the U.S. to re-evaluate its ban on reprocessing as the nuclear genie is already out of the bottle and proliferation risks must be addressed on an international basis. Other nations that are less fortunate with respect to their fossil reserves and are more dependent on nuclear power will proceed with reprocessing whether or not the U.S. continues its self imposed ban. An in-depth assessment of these complex issues is needed now so that the U.S. can complete the necessary research and development work on a schedule that will allow its introduction when needed for low cost energy and low cost waste disposal. It is anticipated that the assessment will confirm that the ALMR/Actinide Recycle System will significantly reduce the demand on the uranium supply and stabilize the price of uranium for future LWRs and that the system will save the U.S. taxpayers billions of dollars in ultimate disposal costs by reducing the size and complexity of the Yucca Mountain repository. The development programs for the ALMR and for the Actinide Recycle System should be continued so that commercialization of the integrated ALMR/Actinide Recycle System can begin as close to the original 2010 date as possible. This will allow the U.S. to take advantage of: (1) the vast energy potential contained in the fissile material contained in present and future stockpiles of spent LWR fuel, and (2) the benefits associated with conditioning the waste prior to placing it in an ultimate repository.

Discussion

Recycling provides for the separation of the materials in the spent fuel assemblies to recover the highly valuable plutonium and uranium which are then used to produce electricity and thus conserve natural resources. The remaining waste can be placed into a form that is more suitable for permanent disposal and which requires a smaller repository volume. This waste management system is consistent with the current societal approach of separating and conditioning other commercial wastes to conserve natural resources and reduce the impact on the environment. While recycling could be used solely to condition the waste, it would not be economical without using the fissile material to create revenue by producing electricity in a nuclear power plant.

Two different systems are available for recycling spent fuel; the aqueous reprocessing system and the electrometallurgical system. The aqueous system was developed by the U.S. Government in the 1950's as the Purex process and was used in several U.S. Government and privately owned plants for reprocessing commercial light water reactor (LWR) fuel prior to the U.S. Government's initial decision in the late 70's to ban fuel reprocessing. This system is currently used to reprocess spent fuel from light water reactors (LWRs) in France, the U.K., Belgium, and Japan. Development of the electrometallurgical processing system (pyro-processing system) was initiated by ANL (funded by the U.S. Government) in the 1970's for recycling spent fuel for liquid metal reactors (LMRs) in the Integral Fast Reactor (IFR) program.

ANL has made excellent progress in developing this system for the recycling of metal fuel for LMRs and has recently modified the system to be capable of recycling the spent fuel from LWRs. This system is known as the Actinide Recycle System. An industry team (GE and Burns and Roe) worked with ANL for the past five years to develop a conceptual design and cost estimate for a future commercial Spent Fuel Recycle Facility (SFRF), which uses the Actinide Recycle System. The SFRF can process the LWR spent fuel and the LMR spent fuel, fabricate new fuel assemblies for use in an Advanced Liquid Metal Reactor (ALMR), and separate the remaining waste into high level and low level waste. The high level waste will be conditioned in the SFRF to produce a low volume, leach resistance product which will minimize the repository cost and reduce the risk of releases of radioactivity to the environment.[2]

The ALMR/Actinide Recycle System is based on the use of an ALMR which has been under development by the industry team for the past ten years. The ALMR is a unique liquid metal reactor design which utilizes passive shutdown, shutdown heat removal, and seismic isolation to simplify the ALMR, improve its safety characteristics, and make it competitive with ALWR plants. The ALMR plant design incorporates the experience gained in the design, construction, and operation of liquid metal reactors in the U.S. and overseas for the past 40 years.

The ALMR design uses a small, factory fabricated modular reactor system which, when coupled with the passive safety features, results in lower capital and operating costs than any other liquid metal reactor in the world. The current design of the ALMR uses a burner core which consumes the plutonium and minor actinides recovered from spent LWR spent fuel. In 1994, the NRC issued a satisfactory Safety Evaluation Report for the plant. The SFRF combines fuel processing, waste conditioning, and fuel fabrication into a small facility which is collocated on the same site as the ALMR power plant. The capital and operating cost of the SFRF is low due to the use of the small, factory fabricated process equipment used in the electrometallurgical process (Actinide Recycle System) and the efficient sharing of systems and equipment.[2]

The ALMR/Actinide Recycle System is economically competitive with the use of ALWRs and their associated fuel cycles. The use of the ALMR in conjunction with the Actinide Recycle System provides for the recycling of the Advanced Light Water Reactor (ALWR) spent fuel at no cost to the ALWR plant owner, while also reducing the cost of the repository required for long term storage of the residual high level waste. The ability to recycle ALWR spent fuel at no cost to the ALWR plant owner (or to the Government) represents a major breakthrough in the economics of spent fuel disposition. Previous studies[3] identified a cost of $1000/Kg of heavy metal to process the LWR spent fuel to separate the plutonium from the fission products in an aqueous reprocessing plant. This resulted in the conclusion that it would cost $86B to process the 86,000 metric tons of spent fuel that will be available from the current generation of LWRs by the year 2020. This made reprocessing of LWR spent fuel appear to be far more expensive than the $32 B estimated cost for the repository.[3]

The ALWR spent fuel can be reprocessed at no cost to the ALWR plant owner or the Government because this cost is covered as part of the 12.4 mills/kW-hr fuel cycle costs for the ALMR power plant that uses the plutonium and minor actinides extracted from the LWR spent as fuel for the ALMR power plant. This generates revenue which covers the cost of the ALMR power plant and the fuel cycle located within the adjacent SFRF.

Recent studies have shown that a symbiosis exists between the ALWR power plant and its current once-through fuel cycle and the ALMR and its associated electrometallurgical actinide recycle/waste conditioning system located in a Spent Fuel Recycle Facility (SFRF). This is shown in Figure 1 as the enhanced fuel cycle.

This symbiosis reduces the cost of the ALWR fuel cycle by providing recycled uranium and by reducing the 1 mill/kW-hr waste fee by eliminating the plutonium and minor actinides from the high level waste to be placed in the repository (reduction in repository cost). The combination of a cost effective Spent Fuel Recycle Facility and a cost effective ALMR power plant results in the ability to produce electricity from this system for busbar costs that are competitive with the ALWR busbar costs (about 40 mills/kW-hr). This cost competitiveness makes it economically feasible to deploy the ALWR/ALMR system so that the plutonium and minor actinides in the ALWR spent fuel can be recycled, thereby substantially reducing the cost of a repository. In addition, deployment of the ALWR/ALMR system provides for considerably greater diversion and proliferation resistance compared to a once-through ALWR fuel cycle, and potential environmental impacts are significantly reduced.

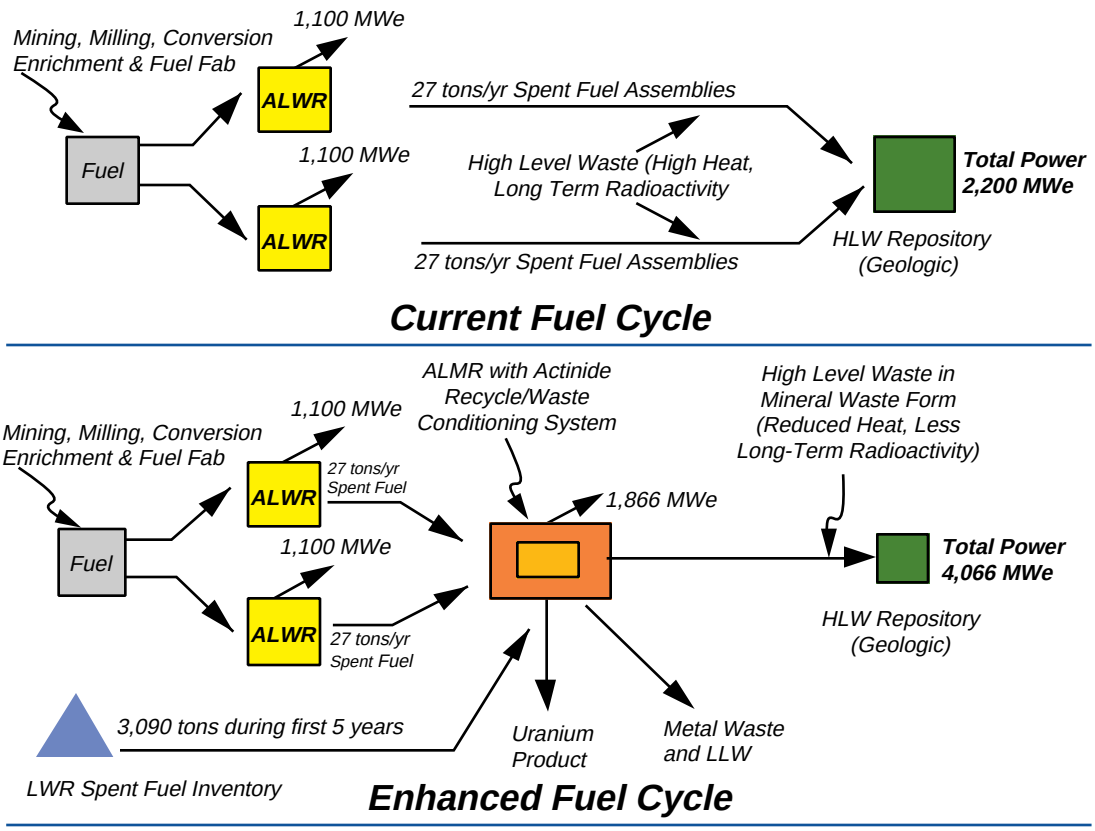

Figure 1. ALWR/ALMR Fuel Cycle.

The currently designed 1,866 MWe ALMR power plant with a burner core annually consumes the plutonium and minor actinides contained in 55 MT of LWR spent fuel. This quantity of LWR spent fuel is discharged annually from two 1,100 MWe ALWR power plants. A comparison of the annual material flow in the fuel cycles for two 1,100 MWe LWRs with a once-through fuel cycle versus two 1,100 MWe LWRs with an 1,866 MWe ALMR and an actinide recycle system in a collocated SFRF is shown in Figure 2.

Table 1 compares the quantities of spent fuel, natural uranium, and enrichment services required by the two systems shown in Figure 1. The fuel cycle is closed by the use of an electrometallurgical process (the Actinide Recycle System) located within the SFRF and collocated on the same site as the ALMR plant. Use of this system reduces the cost of new fuel for the ALWRs by using the recovered uranium to offset some of the cost of mining, milling, and enrichment services associated with new ALWR fuel. The repository cost for disposal of the waste which results from recycling the 55 MT of spent fuel will be lower than direct disposal. Net cost savings relative to the direct disposal of spent fuel in the repository will result from the changes shown in Table 1.

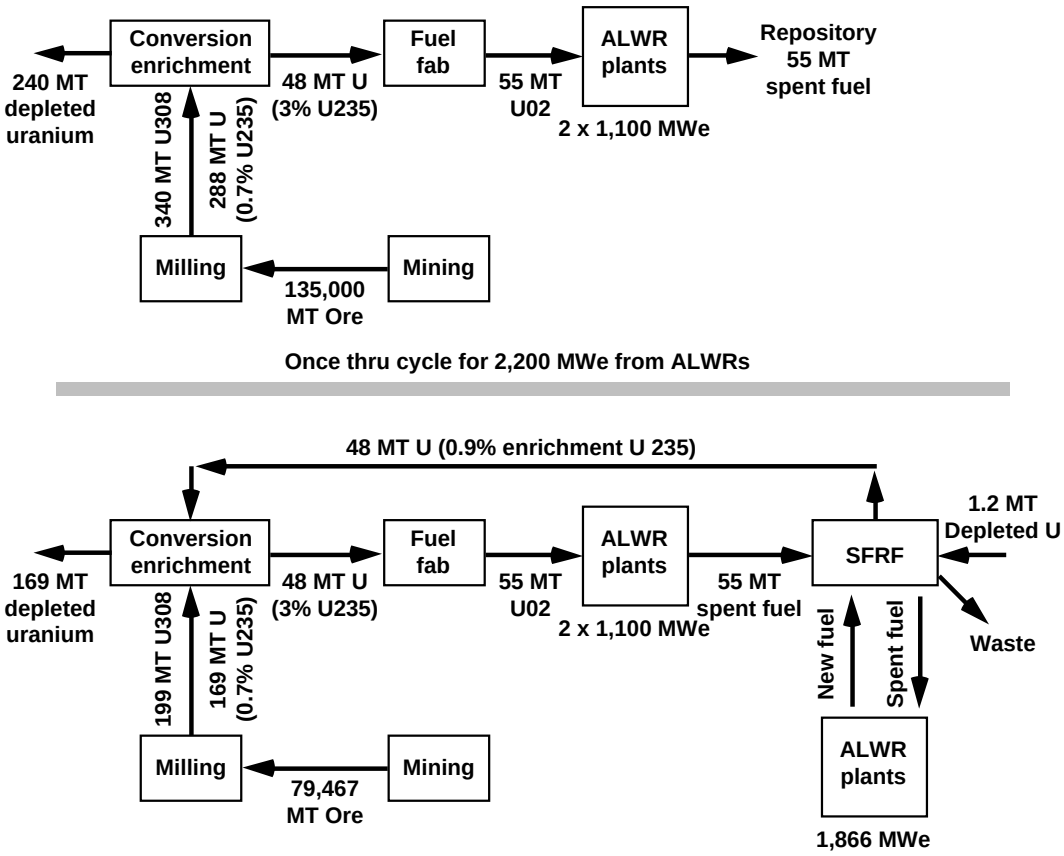

Figure 2. Annual Fuel Cycle Flow Charts.

The ability of the ALMR/Actinide Recycle System to recycle the LWR spent fuel at no cost to the LWR plant owner represents a significant economic breakthrough. All costs associated with the SFRF are included in the fuel cycle busbar costs for the ALMR.

The total busbar cost of the electricity produced by the ALMR is competitive with the cost of electricity produced by an ALWR (including its once-through uranium fuel cycle), so that both the ALMR and ALWR can be deployed in a competitive environment, with all fuel cycle costs fully covered for each system. This is illustrated in Table 2. The use of the ALMR/Actinide Recycle System is compatible with the use of ALWRs which operate on the uranium fuel cycle. The fissile materials can be recycled repeatedly in the ALMR/Actinide Recycle System and thus utilize the fissile material more efficiently (produces more electricity) than once through LWR systems. Recycling the plutonium in an ALMR/Actinide Recycle System permits it to produce far more electricity than it would if it were recycled in an aqueous reprocessing/mixed oxide (MOX) system for reuse in LWRs. The MOX fuel cycle only permits recycling the plutonium two or three times, with

Table 1. Fuel Cycle Comparison.

	Total Power (MWe)	ALWR Spent Fuel to Repository	Natural Uranium Supply	Enrichment Services	ALWR Fuel Fabrication
2,200 MWe from Once Through ALWR	2,200	55 MT Spent Fuel to Repository	288 MTU	184,000 SWU	55 MT UO_2
4,066 MWe from Advanced ALWR/ALMR System	4,066	0 Spent Fuel Sent to Recycle System	169 MTU	162,000 MT SWU	55 MT UO_2
Change	1866 MWe	55 MT	119 MTU	23,000 SWU	Zero
% +/-	85% Increase	100% Decrease*	41% Decrease	13% Decrease	0% NA

* Repository volume required for recycled waste reduced by a factor of four or more.

Table 2. Cost Comparisons (Mills/kW-hr).

	ALMR (1,866 MWe)	ALWR (1,200 MWe)	ALWR (2×1,200 MWe)
Capital	20.0	24.7	22.0
O&M	7.1	7.0	6.5
Fuel	12.4	8.1	8.1
Decommissioning	1.0	1.0	1.0
Total Busbar Costs	**40.5**	**40.8**	**37.6**

spent fuel remaining for permanent disposal. The ALMR/Actinide Recycle System provides for the continued use of the plutonium to produce electricity over many years of plant life.

The ALMR/Actinide Recycle System is more proliferation resistant than the MOX fuel cycle due to the inability of the currently designed commercial Actinide Recycle System to separate plutonium from the other minor actinides and the ability of the ALMR to operate with this mixture of fissile material. This mixture of Pu and minor actinides is not suitable for nuclear weapons. The commercial aqueous mixed oxide (MOX) fuel processing system and the operation of the LWR are based on the separation of the plutonium from the minor actinides resulting in a less proliferation resistant system.

Diversion resistance is enhanced by the unique design of the pyroprocess which uses small simple systems and components which are contained in inerted, shielded cells. These features, together with the batch operation, provides for good accountability and physical protection which reduces diversion risks. The location of fuel recycling and fuel fabrication in a common facility and the collocation of this facility on the same site as the ALMR power plants also reduces diversion risks.

Based on the above discussion, reprocessing ALWR spent fuel in an electrometallurgical recycle system that also recycles ALMR spent fuel and is collocated at the same site as the ALMR power plant is a system can provide for a cost effective nuclear power system for the U.S., with a minimum quantity of high-level waste (with essentially no fissile material) to be placed in a repository. This system also increases the diversion resistance of fissile materials and increases the nation's energy reserves for the future.

Summary

The ALMR/Actinide Recycle System offers multiple advantages and cost benefits to the U.S. nuclear program as described below.

The U.S. Government can avoid spending a large percentage of the projected $30B cost from the Yucca Mountain repository program by conditioning the LWR spent fuel to reduce the long term heat load and permit a four to one reduction of repository storage volume. Removing plutonium and the minor actinides prior to disposal eliminates most of the long lived radioactive material so that concerns about release of this material to the environment over a 10,000 year period can be reduced to a more manageable few hundred year period. Thus, conditioning the waste prior to disposal will save the U.S. Government and the taxpayers billions of dollars by simplifying the analysis required for the environmental impact statement and licensing, and by reducing the effective size of the repository. Use of the plutonium and minor actinides as fuel to produce electricity in the ALMR provides revenue which fully covers the cost of conditioning the LWR spent fuel at no cost to the LWR plant owners.

Preliminary evaluations indicate that up to a 50 to 1 reduction in repository volume is technically feasible by also removing the two elements with the highest heat load (cesium and strontium) from the waste stream prior to disposal. Further development work is required to confirm that this additional processing step is economically justified, but further reduction in repository cost may be possible.

The use of the plutonium and minor actinides that can be extracted from the LWR spent fuel and used to produce electricity with an ALMR significantly reduces the demand on the uranium supply thereby helping to stabilize the price of uranium at the current low levels. Utilizing the uranium recovered from the spent LWR fuel to make new LWR fuel reduces its near term fuel cost while also reducing the demand for uranium and stabilizing the price.

Spent LWR fuel from the current generation of LWRs can be removed from the interim storage facility or from utility fuel pools at a rate commensurate with the deployment rate of the ALMR/Actinide Recycle System. The total 86,000 metric tons (MT) of this inventory that will be accumulated by 2020 can be used for the startup of about 40 ALMR plants. A deployment rate of one ALMR/Actinide Recycle System per year permits depletion of this inventory in 40 years. By the use of burner cores, the continued operation of the ALMRs can utilize the spent fuel from future ALWRs to avoid a buildup of inventory of LWR spent fuel in the future. This provides for prompt utilization of the plutonium contained in the ALWR spent fuel and improves the fuel cycle economics while reducing the proliferation potential.

The ALMR/Actinide Recycle System keeps the plutonium and minor actinides that are removed from the LWR spent fuel fully contained within a closed loop consisting of a reactor and a fuel recycle facility located on the same site. This provides a system which is highly resistant to diversion and proliferation and can meet all IAEA and NRC safeguards, security, and accountability requirements.

Early deployment of the ALMR/Actinide Recycle System provides for stability of the fuel cycle costs (front end and back end costs) throughout the 40 year operating lifetime of the future ALWRs. This stability is an important aspect in the future use of nuclear power in the U.S.

Conclusion

Progress on the development of the ALMR/Actinide Recycle System has been excellent, with no major problems identified. However, funding for development of the ALMR power plant and the Actinide Recycle System was eliminated by Congress in 1994 in response to an initiative by the Executive Branch.

The five billion dollar cost to complete the development of the ALMR/Actinide Recycle System can be funded through Government/industry cost sharing since all parties can derive future cost benefits that far exceed the development costs.

The ALMR/Actinide Recycle System also has the potential to provide an almost limitless supply of energy in the future. This is achievable by reconfiguring the ALMR core to breed more plutonium than it consumes by using the vast stockpiles of depleted uranium as an energy source. This may be considered later in the 21st century if uranium supplies for ALWRs become too expensive and if other more economical energy sources fail to materialize.

Related Activities

Following the Global 95 Meeting in Versailles, France in September, 1995, two other papers were presented on this topic:

"Cost Effective Fuel Cycle Closure," by C. Ehrman (Burns and Roe) and C. Boardman (General Electric) presented at the American Nuclear Society, Winter Annual Meeting in San Francisco on November 1, 1995 (Vu-Graphs also provided).

"Integrating ALWR and ALMR Fuel Cycles," by C. Boardman (General Electric), M. Thompson (Consultant), C. Ehrman, C. Hess, M. Ocker (Burns and Roe) presented at the ASME/JSME ICON-4 Meeting in New Orleans on March 11, 1996 (Vu-Graphs also provided).

From October, 1995 to March, 1996, a draft of the National Academy of Science STATS Committee report on Separation and Transmutation of LWR spent fuel was reviewed by the authors of the papers noted above, plus C. Walter of Lawrence Livermore National Lab, and H. Bengledorf, B. Wolfe, K. Davis and others. Comments were submitted to the STATS Committee requesting revision to the report to include the information about the use of the ALMR Actinide Recycle System to process the LWR spent fuel in a cost effective manner as discussed in this report. Unfortunately, the final STATS report issued in March, 1996 does not provide the current perspectives on the ALMR Actinide Recycle System. Further efforts will be made to inform others of the advantages of the use of the ALMR Actinide Recycle System to utilize the plutonium in the LWR spent fuel and avoid disposal of it in a repository.

It is noted that since the March 1995 completion date of the DOE contract with the GE Design Team for work performed on the ALMR Actinide Recycle System, none of the work involved in preparing and presenting papers was done under DOE contract. The work was performed largely at the expense of each individual noted above.

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1. Quinn, J.E., "Realizing the World Economic, Environmental, and Non-Proliferation Benefits of the ALMR Actinide Recycle," The International Symposium on Global Environmental and Nuclear Energy Systems, Shizuoka, Japan, October 24-27, 1994.
2. Ehrman, C.S., Hess, C.W., Ocker, M.T. (Burns and Roe Co.), "Design Considerations for a Pyroprocess Recycle Facility," Presented at Global 95 Meeting, Versailles, France, September 1995.
3. Ramspott, L.D., Choi, J., Halsey, W., Ponsternak, A., Cotton, T., Burns, J., McCabe, A., Colglazier, W., and Lee, W.W.L, *Impacts on New Developments in Partitioning and Transmuting on the Disposal of High-Level Nuclear Waste in Mined Geologic Repository*, UCRL-ID 109203, Livermore, CA, Lawrence Livermore National Lab, 1992.
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A Strategy For an Advanced Nuclear–Electric Sector— Proliferation-Resistant, Environmentally-Sound, Economical

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Abstract

A strategy is proposed for deployment of an advanced nuclear-electric power sector that is ultimately fueled only by recycled or depleted uranium. The sector is optimized on a system basis to meet several objectives in the context of international safeguards against diversion of plutonium and proliferation of nuclear weapons. These objectives include (1) generation of electric power efficiently and economically; (2) performance with utmost predictable safety; (3) minimization of environmental impacts through conservation of natural resources, consumption of actinides and long-lived fission products, and responsible disposal of unavoidable waste; and (4) consumption of spent fuel from currently used reactors.

Introduction

It is important to recognize that the deployment strategy for an optimum electric power sector in the U.S. must be applied in a national system context. The entire nuclear-electric power sector must be considered as an entity. Only extensions of existing technologies pertaining to fast nuclear reactors and a modest research and development program are required. Deployment of such a system should be initiated with a sense of urgency. This urgency stems from the coincidence of several events: (1) need to establish national energy independence to reduce world strife, (2) need for conservation of world oil resources, (3) public realization of the stress on the world environment that results from the use of fossil fuels, (4) continued lack of progress in establishing an acceptable reactor spent fuel storage strategy (in the U.S. as well as the rest of the world), and (5) the continuing need for utmost protection from diversion of plutonium from the nuclear fuel cycle.

Electricity Generation in the U.S.

World-wide energy needs over the next half-century (and beyond) will increase significantly. In particular, world electricity generation is projected to increase from 11-13 petawatt-hours per year (PWh/y, = 10^{12} kWh/y) in 1995 to 20-29 PWh/y in 2025 and 31-50 PWh/y in 2050.[1] These variations in energy depend on assumptions made in the projections relative to energy efficiency and emission controls. The lower values represent an average annual growth of electricity generation of 2%, while the higher values represent 2.7% annual growth. Over the same time period the medium estimate of world population annual growth is

slightly over 1%.[2] The estimates of electricity generation consider that the energy sources in 2050 will be largely (60%) renewable: wind, direct solar, biomass, and hydro. The absolute nuclear contribution is considered to remain essentially constant through this period.

Although the U.S. is already a "developed" nation, its electricity generation is also expected to increase– from just under 3.0 PWh/y in 1995 to 4.1 PWh/y in 2010.[3] This increase in generation represents an annual growth rate of 2.1%. During this period the population in the U.S. will most likely grow at an annual rate of 0.8%.[4] A higher rate of electricity generation per capita has been shown to correlate with improved national economic strength. On the downside, unless the increased amount of electricity is produced in an environmentally benign way, the quality of life will tend to deteriorate.

It does not seem reasonable to expect that photovoltaic, wind, and hydro power can provide all the world needs for electricity during the next century. Even strong proponents[2] of renewable energy agree on this point. Nuclear power must represent a substantial fraction of the electricity generated if the environmental effects of coal-fired electricity are to be avoided. At present, emissions of the "greenhouse" gases (carbon dioxide and nitrogen oxide) from transportation sources and electric utilities are comparable, although transportation produces far more carbon monoxide, nitrous oxides, and methane emissions.[5] Transportation emissions could be significantly reduced with increased reliance on electric-powered transportation, provided that the electricity is not generated by fossil-fueled plants. Such a change in transportation would further increase the demand for electricity. In the U.S., for example, depending on the efficiency and extent of electric transportation, an increase of 50% in electricity generation over currently predicted amounts could result.[6] As can be seen from the world and U.S. comparative electric power estimates stated above, the benefits of an optimum U.S. nuclear power sector solution could be amplified world-wide by a factor of about four. Deployment of an optimum nuclear power sector thus merits a high-priority national effort that could also provide a world benefit.

Nuclear Power in the U.S.

Currently (1995) there are 109 commercial light water reactors (LWRs) in operation in the U.S. with an installed capacity of 99.5 GW_e.[7] At the end of 1995, the cumulative discharge of spent fuel from U.S. LWRs will be 32,300 t and will increase to 84,500 t by 2030 in the case of no new reactor orders.[8] The potential electric power production capability of the accumulated plutonium inventory remaining in all the LWR spent fuel in this scenario, discounting amplification in uranium (or thorium), is about 6 PWh, or about one and a half times the total U.S. electric power estimated to be needed in 2010. It seems imprudent to waste such a large energy resource by burying it in a mined geologic repository. Not only would its energy be lost, but the plutonium would continue to be a potential source of nuclear weapon material well into the distant future.

Table I shows the potential power deficit in the nuclear-electric power sector as the LWRs reach their design life and are retired. It is proposed here to avoid this deficit by replacing retired LWRs with advanced liquid metal (fast) reactors (ALMRs) as shown in Fig. 1. The scenario examined here assumes a constant nuclear power sector of 100 GW_e. An increasing nuclear power capacity is more likely however, in view of the predictable growth in electricity demand, the adverse environmental consequences of fossil plants, and the dim prospects for cost-competitive, ubiquitous, renewable energy electric plants.

ALMRs would be fueled, initially, with all of the plutonium and some of the uranium reclaimed from the LWR spent fuel. The last three columns of Table I show the cumulative quantities of plutonium, respectively, that could be separated from discharged LWR fuel, that would be needed for ALMR inventories, and that represent the net oversupply. The last column indicates that there is not quite enough plutonium from this source to fuel all the ALMRs needed to make up the LWR power deficit. Figure 2 shows the supply and demand characteristics for 40-y and 60-y life LWRs. The balance of supply and demand can be achieved in several ways. By operating the LWRs over a 60-y period, as shown in Fig. 2, the supply and demand are equal. Life-extension programs for some LWRs are being considered. Another possibility is to build and operate a few more LWRs. The easiest resolution, however, is offered by utilization of more than sufficient surplus quantities of highly enriched uranium (HEU)) in the U.S. and in Russia. The U.S. has contracted to purchase 500 t of HEU from Russia for use in LWRs. If used in ALMRs, HEU is roughly equivalent on a mass basis to plutonium. Also, about 50 t of weapon plutonium could be declared excess to U.S. national defense needs.

Table I. Accrual of plutonium from discharged LWR fuel and plutonium requirements for fueling replacement ALMRs.[7,8,10*]

Year	Installed LWR Power, GW_e	LWR Power Deficit, GW_e	LWR Spent Fuel, 10^3 t	LWR Discharged Pu, t	ALMR Inventory Pu, t	Net Available Pu, t
1995	99.5	0	32.3	290.7	0	290.7
2000	99.5	0	42.3	380.7	0	380.7
2005	99.5	0	51.9	467.1	0	467.1
2010	97.6	1.9	61.9	557.1	21.6	535.5
2015	72.2	27.3	71.0	639.0	313.9	325.1
2020	53.9	45.6	76.7	690.3	523.8	166.5
2025	37.5	62.0	82.1	738.9	712.4	26.5
2030	4.5	95.0	84.5	760.5	1092.3	-331.8
2035	0	99.5	85.6	770.4	1144.1	-373.7

*Assumptions: (1) LWR spent fuel has a Pu concentration of 0.9%, (2) The ALMR/fuel- cycle plutonium inventory is 11.5 kg/MW_e, (3) LWRs operate over a 40-y life.

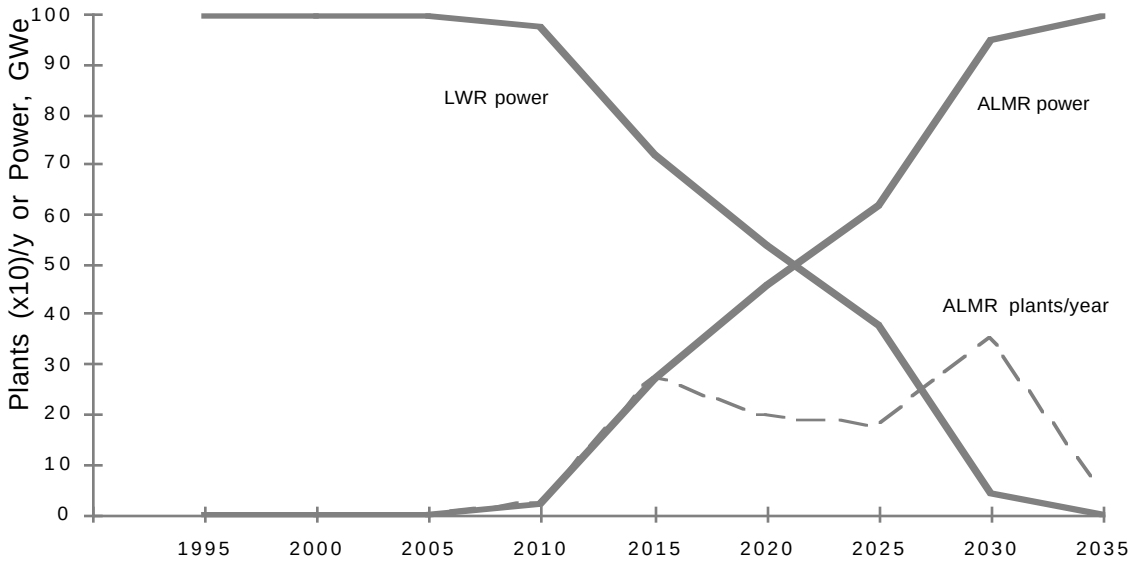

Figure 1. Relationship of LWR power and ALMR power assuming a 40-y design life of LWRs and a constant nuclear power sector (99.5 GW_e). The annual rate of 1818-MW_e ALMR plant construction is also shown.

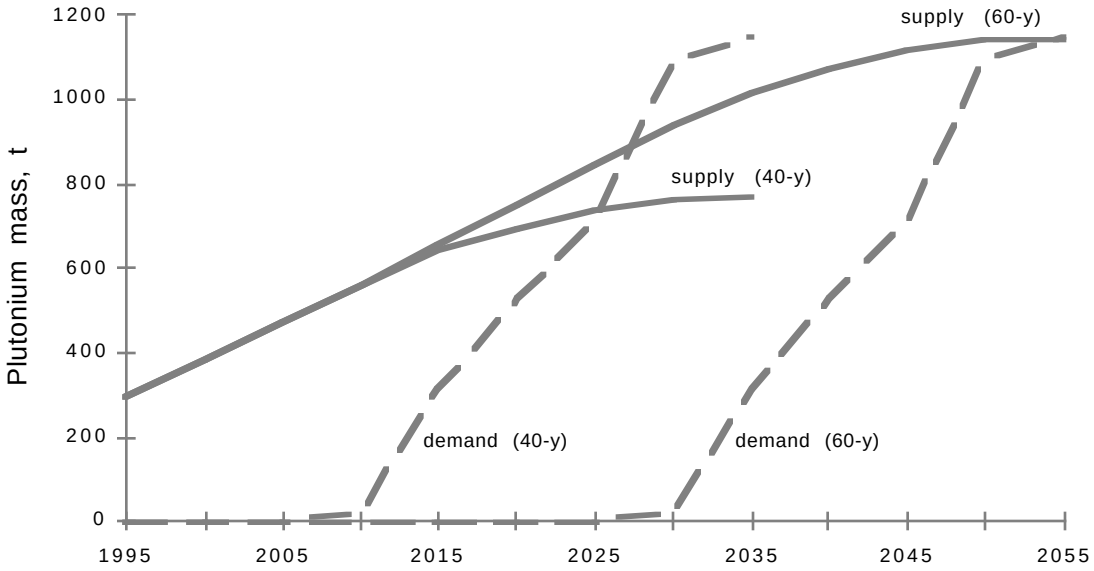

Figure 2. Supply of plutonium from spent fuel for present LWRs (40-y and 60-y design life) and the demand requirements for ALMRs that would replace the LWRs.

ALMR Advantages

The course of nuclear reactor technology was influenced by the early strong leadership of Admiral Rickover during the development of pressurized water reactors for U.S. submarines. As a result, these, together with boiling water reactors, constitute the bulk of the world's LWRs. While LWRs may be the best technology for submarines, they are not necessarily an optimum solution for commercial power generation. This is particularly the case when considered in a system context, i.e., the complete power generation process including obtaining the fuel and disposing of the waste. These issues were of minor concern in the Navy program.

The possibility of breeding fissile material is greatly enhanced in a fast (unmoderated) reactor. Recognition of this characteristic led to the early development of sodium-cooled, fast reactors, all of which have performed well. About 20 fast reactors have been built since 1956 throughout the world and have operated safely. Most have been sodium-cooled. Two examples are the 20-MW_e Experimental Breeder Reactor (EBR II) in operation over 30 y in the U.S. and the 1240-MW_e SuperPhenix reactor that began operation in France in 1985. In the U.S. a vigorous five-year research and development program in support of the ALMR was recently mandated by Congress,[9] but to date has not been executed.

The conversion ratio in a fast reactor (ALMR) refers to the ratio of the plutonium produced in uranium to the amount of plutonium fissioned. This ratio is adjustable by core design.[10] The reactor can be tailored to make use of excess neutrons in various ways. Initially, the potential for breeding more fuel than was consumed was considered the most significant advantage of the fast reactor. Early power-sector scenarios envisioned a mix of LWRs and fast reactors operating at a conversion ratio greater than one. The fast-reactor spent fuel would be reprocessed and incorporated into fresh fuel for the fast reactor and a number of LWRs. Alternatively, the reactor can be operated at a conversion ratio of 1.0, with no net production of fissile material. A conversion ratio of 1.0 applies to a constant capacity nuclear power sector consisting only of ALMRs.

ALMRs have a number of advantages over LWRs: (1) actinides are fissioned or transmuted and subsequently fissioned in fast-spectrum regions, (2) long-lived fission products can be transmuted to shorter half-life isotopes in thermalized regions, (3) the equation of state of sodium permits higher reactor coolant outlet temperature at low ambient pressure, thus enhancing thermal efficiency and safety (4) cores are typically ~1/3 shorter, thus facilitating remote fuel fabrication, (5) use of metallic fuel elements (vs. LWR oxide fuel) with improved thermal conductivity also simplifies fuel fabrication, and (6) in the steady state, with a conversion ratio of 1.0, the reactor consumes its own long-lived waste and requires only addition of uranium (U-238) as a fertile source of plutonium.

Three sources of fertile material (uranium) in ALMR fuel may be considered: recycled uranium from spent LWR fuel, depleted uranium in enrichment tails, and newly mined natural uranium. The amounts of these resources are shown in Fig. 3.

Logically, these sources of uranium would be selected in the order stated. Recycled uranium would suffice essentially indefinitely. As can be seen from Fig. 3, less than 10% of the uranium in the accumulated LWR spent fuel in this scenario would be needed for the initial inventories and makeup for a 100-y operation of a 100-GW_e ALMR power sector. The remainder could be used for fueling the retiring complement of LWRs in the U.S. and for foreign reactors. The depleted-uranium stockpiles (enrichment tails) contain several times the mass of uranium in the spent fuel to be discharged from LWRs under this scenario and would likely not be needed for ALMRs. Thus, by recycling uranium as soon as possible for use in LWRs, further mining of uranium could be minimized. Eventually, no further mining or enrichment of uranium would be required to support the nuclear-electric power sector.

Growth of demand for electricity would be accommodated by appropriate adjustment of the conversion ratio in all or selected ALMRs. The additional plutonium produced in this manner would be aggregated to provide first-core inventories for new ALMRs as needed. Uranium could be provided from recycled or depleted supplies.

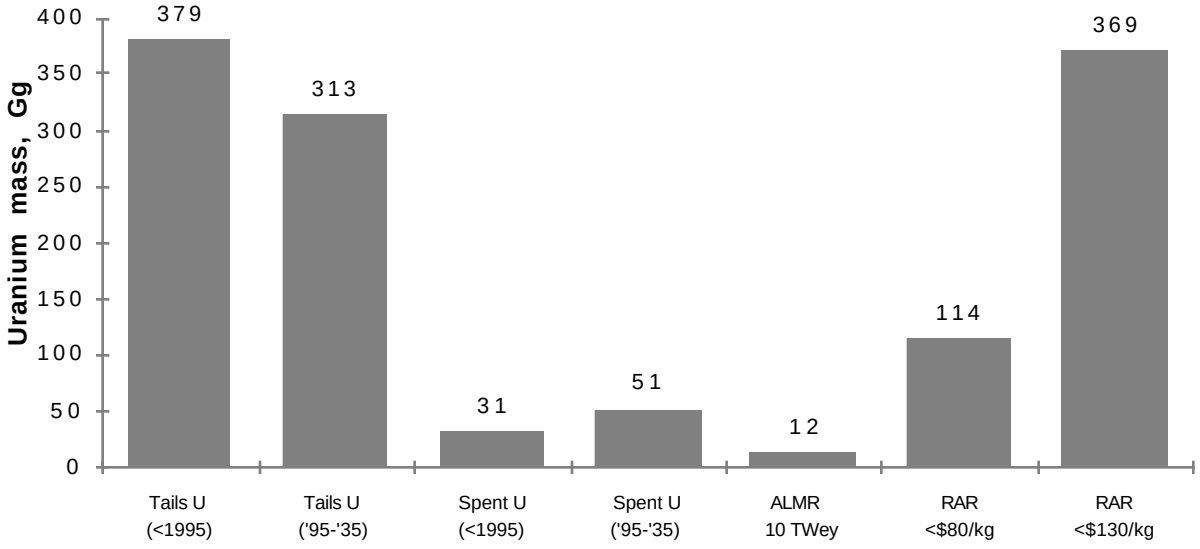

Figure 3. Amounts of uranium contained in enrichment tails, spent LWR fuel, and reasonably assured resources (RAR) in the ground. The amount of uranium required to fuel a 100-GWe ALMR sector for 100 years is shown for comparison.

Non-Proliferation Aspects of ALMRs

How to dispose of excess plutonium from dismantled nuclear weapons is a fundamental issue that remains unresolved. Central to this issue is determination of what constitutes disposition. The objective of disposition is clear—to prevent the reuse of plutonium in a nuclear explosive. But there is no certain way of assuring this, short of its annihilation. Further, it appears that the stockpile of plutonium isotopes contained in commercial spent fuel, when separated from the spent fuel, is not much more difficult to use for a weapon than the isotopes present in weapon plutonium. Therefore, to avoid proliferation of nuclear weapons, one must consider both excess weapon plutonium and the plutonium present in commercial spent fuel– worldwide! This subject was thoroughly considered by the U.S. National Academy of Sciences.[11]

There is a solution to this fundamental issue: Accountability of all the plutonium in co-located reactor and fuel facilities would be maintained under International Atomic Energy Agency (IAEA) safeguards. At equilibrium, the incoming fuel-feed material to the ALMRs is recycled, depleted, or natural uranium and the outgoing material (waste) consists of encapsulated short-half-life fission products with negligible actinide impurities. No weapon-capable material would be transported in or out of the power plant. This technology is well represented by the ALMR with integral fuel recycling (IFR) capability as discussed in other papers presented at the Global '95 conference.[12]

Fuel would be recycled in facilities adjacent to the ALMRs using pyrochemical and electrorefining processing methods. Considerable process improvements have been made recently. These improvements not only produce a better product, but the cost is greatly reduced. Detailed cost studies have been performed, and it appears[13] that the costs of power from ALMRs and LWRs would not differ significantly. Of particular importance to this discussion is the inherent proliferation resistance of the process. When the material being processed is LWR spent fuel, three products result: metallic plutonium with <u>all</u> the minor actinides, pure metallic uranium containing less than 1% U-235, and fission products containing essentially no actinides. The presence of the minor actinides in the plutonium makes it unusable directly for a nuclear explosive, as the minor actinides produce heat and preclude, or greatly impede, the construction of an explosive device. The uranium product contains a fissile fraction that is not much different from that of natural uranium and is therefore not attractive for weapons. The plutonium product and part of the uranium product would be used to fabricate ALMR fuel.

When ALMR fuel is being recycled, two products would be produced: metallic uranium containing plutonium, <u>all</u> the minor actinides, and some of the rare-earth fission products; and fission products containing essentially no actinides. The former product would also contain zirconium, as the metallic fuel developed for use in the ALMR is typically 70% U, 20% Pu, and 10% Zr. The plutonium fraction in heavy metal could slightly exceed 20%,[10] but the presence of the minor actinides

and rare-earth fission products would provide an effective proliferation barrier. Uranium obtained from earlier LWR spent fuel processing would be added in fabricating the ALMR fuel to compensate for the uranium that is converted to plutonium during operation of the reactor.

In the proposed scenario, at no time does pure separated plutonium exist. As stated before, in addition to the actinides, some of the short-half-life rare-earth fission products also carry through with the plutonium and provide a significant radiation barrier for a few years. Fresh plutonium-bearing fuel would not be transported on public roads at any time, as each complex of ALMRs would have IFR capability. Material protection, control, and accountability would be easily implemented under stringent provisions for safeguards and security under IAEA inspection.

Environmental Considerations

The ALMR/IFR nuclear-electric power sector can be phased-in gradually as LWRs are retired and thereby maintain the current nuclear capacity. This can be done in conjunction with useful exploitation of LWR spent fuel and simultaneously solving the environmentally troublesome spent-fuel disposal problem. Uranium enrichment, with its attendant creation of large volumes of depleted uranium and high power consumption, would no longer be required after the last LWR is retired. No more mining and milling of uranium would be required. Additional electricity demands could be easily accommodated without resorting to the use of fossil fuels. World-wide expansion of the use of ALMR/IFR technology would likewise ameliorate the current environmental issues with nuclear power.

Eventually, as a better source of electricity is found, the plutonium inventory in the resulting nuclear power sector could be reduced in a systematic manner. Essentially complete annihilation of plutonium could be accomplished if and when nuclear power is no longer needed.

Strategy for Transition to an ALMR/IFR Power Sector

In the U.S., the plan for many years has been to carefully store commercial spent fuel in an essentially irretrievable manner in a geologic repository for perpetuity**.** Although a greater effort is being expended today than 50 or even 20 years ago, little progress has been made. But even rapid progress is not likely to yield a satisfactory solution. The approach being taken suffers from a fatal flaw: no person, institution, or government can be held accountable for a malfunction of a mined geologic repository for even a minuscule fraction of the time (over a million years) that the warranty must be valid. Faced with this situation, a different approach must be devised and implemented by a responsible society. By proper consideration of all the objectives of power generation, an optimum nuclear electric power sector can be described. Competing systems (fossil, renewable, etc.) also must

be evaluated on an overall sector basis. Only then can a reasoned approach be taken to provide the electric power that a nation must have to maintain a high standard of living.

A strategy applicable to the U.S. nuclear-electric power sector is proposed here. A similar strategy could (and should) be developed for other nations. Implementation of the proposed strategy should be privatized as much as practicable. It would be advantageous, however, to have governmental support to initiate the strategy and demonstrate the first ALMR/IFR facility in the U.S.

Step 1. Construct an appropriate receiving and interim storage facility for spent fuel from U.S. reactors. The U.S. government has agreed to accept spent fuel from the utilities beginning in 1998. A logical location for acceptance of this material is at the Department of Energy's Nevada Test Site which is adjacent to the Yucca Mountain Site being investigated as a potential permanent geologic repository for spent fuel and other high level waste. This would be a convenient staging area if in fact the Yucca Mountain Site is later selected to be a repository and it is determined that burying spent fuel is indeed the optimum solution. Toward this end, legislation was introduced in the U.S. Congress early this year.[14,15]

Step 2. Transport all LWR spent fuel (after appropriate cooling) to the Nevada Test Site (NTS) for interim storage.

Step 3. Design and construct an ALMR power plant located at the Nevada Test Site. In 2010, the current LWR power deficit would be 1.9 GW_e (see Table I). This power deficit could be offset by a six-unit ALMR modular power plant, with each unit producing 313 MW_e. Fortuitously, this is the size of a modular ALMR plant being considered in the U.S.[10] This time frame for startup of the first ALMR power plant seems reasonable, both from the standpoint of reactor construction and construction of the integral fuel recycling (IFR) facility (Step 4).

Step 4. Design and construct an IFR facility based on pyrochemical processing utilizing solvent electrorefining. At first this facility would be used to partition LWR spent fuel into three product streams as described above. Whether or not the LWR spent fuel form is eventually found to be acceptable in the adjacent potential Yucca Mountain repository, the fission product stream should be readily acceptable as its hazardous life is about 300 y and it has no nuclear weapon proliferation capability. This is in contrast to about 0.3×10^6 y for essentially all of the Pu-239 in spent fuel to decay to U-235, during which time proliferation concerns at the repository would continue. The plutonium stream would be loaded into adjacent ALMRs (see Step 3) with only a short interim storage time. A small fraction of the uranium stream (containing less than 1% U-235) could be used directly for fabricating ALMR fresh fuel and the remainder could be combined with highly enriched uranium (HEU) for use in LWRs with remaining life. Eventually the IFR facility would process only ALMR spent fuel and recycle the transuranics and the uranium. Makeup uranium would be withdrawn from stocks resulting from

earlier recycling of LWR spent fuel and eventually from the vast stockpiles of uranium enrichment tails.

Step 5. Conduct a system optimization study to establish the optimum power capacity at the Nevada Test Site for the Western U.S. grid. Because of its location in southwestern U.S. the Nevada Test Site is well-positioned for a nuclear power park. The study should be expanded to consider other sites in the U.S. that would also be suitable for ALMR/IFR complexes. The study should address means for maintaining private ownership of the elements of the nuclear-electric power sector.

Step 6. Develop a sunset plan for the ALMR/IFR nuclear-electric power sector. Eventually a better way of producing electricity may become available. There must be a responsible plan for eliminating the plutonium inventory that will reside in the ALMR/IFR complexes. Obvious solutions include operation at conversion ratios less than one and replacing uranium with a non-fertile material in fresh ALMR fuel. Eventually, the remaining plutonium would be consolidated in only one ALMR. Special means for annihilation of the remaining plutonium in the last ALMR module would need to be devised.

Conclusions

The ALMR/IFR approach to nuclear power appears to resolve the energy resource, proliferation, environmental, and economics issues that are of concern. There is a logical step-by-step strategy for achieving a nuclear electric power sector that provides the U.S. and the world a sound method for meeting a growing demand for electricity. A strategy for systematic retirement of LWRs as they complete their design life and their replacement with ALMRs with integral fuel recycle capability appears to be feasible.

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Depleted Uranium Hexafluoride: Waste or Resource?

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Abstract

The U.S. Department of Energy is evaluating technologies for the storage, disposal, or re-use of depleted uranium hexafluoride (UF_6). This paper discusses the following options, and provides a technology assessment for each one: (1) conversion to UO_2 for use as mixed oxide fuel, (2)conversion to UO_2 to make DUCRETE for a multi-purpose storage container, (3)conversion to depleted uranium metal for use as shielding, and (4)conversion to uranium carbide for use as high-temperature gas-cooled reactor (HTGR) fuel. In addition, conversion to U_3O_8 as an option for long-term storage is discussed.

Introduction

In the United States, uranium enrichment is currently accomplished through a process known as gaseous diffusion. In this process, gaseous uranium hexafluoride (UF_6) is separated into two streams—one enriched in Uranium-235 (U-235) and the other depleted in U-235. The U.S. has produced enriched uranium on a large scale using gaseous diffusion technology since the 1940s. Until very recently,[*] the U.S. Department of Energy (the Department) was responsible for the uranium enrichment enterprise in the United States.

A major consequence of the gaseous diffusion process is the accumulation of a significant amount of depleted UF_6. Although ratios may vary in practice, producing one pound of UF_6 enriched to 3.0 percent U-235 will typically result in 5.5 pounds of depleted UF_6 at 0.3 percent U-235. This depleted UF_6 is stored as a solid in a partial vacuum in 10- to 14-ton steel cylinders with 5/16 inch- (0.794 cm-) thick walls. The majority of the cylinders are approximately 12 feet (3.65 m) long

[*] In October 1992, the Energy Policy Act of 1992 created the United States Enrichment Corporation (USEC), and required the Department of Energy tp lease the Portsmouth and Paducah Gaseous Diffusion Plants to the USEC effective July 1, 1993. The Department retains responsibility for the depleted UF_6 produced prior to July 1, 1993.

and 4 feet (1.22 m) in diameter. Currently, this inventory occupies a total of about 47,000 cylinders containing approximately 560,000 metric tons of UF_6.

Development of a Management Strategy for Depleted Uranium Hexafluoride

The unique properties of depleted UF_6, as well as the large volumes in storage, suggest that a careful evaluation and analysis of potential management strategies for the long term disposition of this material may result in the application of technologies and/or end-uses not previously considered. In an effort to develop a cost-effective, energy-efficient and environmentally safe management strategy for the disposition of this material, the Department has initiated an innovative program to include the public and private industry in the recommendation and evaluation of various technologies for the potential storage, disposal, or re-use of this material. The technology assessment portion of this program was completed in June 1995. This paper will discuss the elements of the technology assessment, including the Department's request for recommendations, the evaluation criteria used for the assessment, and an analysis of various end-uses applicable to the nuclear fuel cycle.

Request for Recommendations and Technology Assessment

On November 10, 1994, the Department published a notice in the *Federal Register* (FR 56324), asking individuals, industry, and other government agencies to submit suggestions for potential uses for depleted UF_6, as well as for technologies that could facilitate the long-term management of the material. The Department specifically requested recommendations for the following: (1) uses or applications of products or materials that include any form of depleted uranium and (2) technologies that could facilitate the long-term management of depleted uranium. The uses or applications could be for depleted uranium in its current chemical form (UF_6); for any of its individual components; for either the uranium or the fluorine in some other chemical or physical form; or for products made from any form or compound of depleted UF_6 including alloys, cements, or other materials. The deadline for submittal of recommendations was January 9, 1995. Fifty-seven responses containing 70 recommendations were received. Lawrence Livermore National Laboratory (LLNL) was chosen by the Department to conduct the technology assessment of these recommendations. LLNL assembled a group of Independent Technical Reviewers (ITRs) to assist in the assessment. The ITRs were selected based on experience in areas such as process technology, uranium processing and fabrication, engineering finance/economics, environmental engineering and waste management, hazards analysis, and environmental regulations. Using the evaluation factors described below and their own individual expertise, the reviewers assessed the technical feasibility of each recommendation.

Evaluation Factors

Evaluation factors were developed by Lawrence Livermore National Laboratory with input from the public to serve as guidelines in the conduct of the technology assessment. Six evaluation factors were considered in the assessments:

A. Environment, Safety and Health. This factor considers issues of concern to workers, the public and the environment such as: issues that may arise as a result of operations, transportation, handling, storage, and disposal, including effluents and emissions; issues that may restrict site choices when constructing or operating a facility that employs a specific technology or application; and design configurations, specifications, or operational requirements that pose problems of nuclear, chemical, or other safety issues involving workers or the public.

B. Waste Management. While related to Factor A, waste management was evaluated separately due to its potential significance. This factor included radiological, nonradiological, hazardous, toxic, mixed, or solid waste streams and waste volumes, or residual material that may pose problems of storage, transportation, treatment, or disposal; the potential for waste minimization in use or manufacture; and potential for recycling.

C. Costs. Consideration was given to costs which are associated with the development or use of a specific technology or with the use of a product, or which could preclude consideration of a recommendation. These include: capital costs, both initial, including research and development (R & D) and continuing; annual operating and maintenance costs; decontamination and decommissioning costs; value of any product or facility salvage; and cost avoidance through the sale of any byproducts.

D. Technical Maturity. For new technologies, issues such as time to availability and probability of success were considered by evaluating the following developmental stages: design - conceptual or detailed; bench or small scale; developed but untested on a large scale; tested or used on a large scale, but not standard industrial practice; or standard industrial practice.

E. Socioeconomic. Consideration was given to the effect of recommendations on socioeconomic indicators such as employment, public acceptance, and local or regional economic development.

F. Other. This factor included any other information believed pertinent to the feasibility of a submission.

Evaluation of Four Nuclear Fuel Cycle End-Uses

Table 1 summarizes several options for the use of depleted UF_6. From the many recommendations submitted to the Department, four potential fuel cycle end-uses were chosen as examples for this paper: (1)conversion to UO_2 for use as mixed oxide fuel, (2) conversion to UO_2 to make DUCRETE for a multi-purpose storage container, (3) conversion to depleted uranium (DU) metal for use as shielding, and (4) conversion to uranium carbide (UC) for use as high-temperature gas-cooled reactor (HTGR) fuel. Each of these alternatives requires conversion to another form such as an oxide or metal. In addition, the conversion to U_3O_8 is discussed as an option for long-term storage. The following section will generally discuss the uranium processing techniques and provide an assessment of each of these end uses based on the previously described evaluation factors and input from the ITRs.

Conversion to UO_2

The conversion of UF_6 to ceramic UO_2 is industrially practiced in the fuel fabrication industry. Either by a "wet" or "dry" process, the UF_6 is converted to a UO_2 powder under carefully controlled conditions to assure suitable powder morphology. The pellet is then pressed under high pressure, and finally sintered to yield a solid which is typically 95% of the theoretical density. UO_2 in the ceramic form as pellets or small particles has a density several times that of normally compacted UO_2 or U_3O_8 powders.

There are two conventional wet processes commonly used for conversion of UF_6 to UO_2. The ammonium diuranate (ADU) process involves the hydrolysis of UF_6 to UO_2F_2 followed by the addition of ammonium hydroxide to precipitate the uranium and ammonium diuranate, $(NH_4)_2U_2O_7$. After centrifuge separation from the liquid, the ADU slurry is dried. The ADU is calcined to uranium trioxide, and then reduced with hydrogen to UO_2.

The ammonium uranyl carbonate (AUC) process is also a precipitation process, and was developed to reduce the number of steps associated with the ADU process. The UF_6 is hydrolyzed to uranium fluoride, and, through the addition of ammonia and carbon dioxide, the uranyl fluoride is precipitated as ammonium uranyl carbonate $(NH_4)_4U_2O_7CO_3$. After filtration and drying, the AUC is calcined in the presence of hydrogen to UO_2. The oxide is subsequently pressed and sintered.

In recent years, fuel fabricators are increasingly turning to dry routes when replacing or expanding capacity. The dry route has substantially fewer steps and fewer waste management issues than the wet routes. As in the case with the wet processes, there are several variations of dry processes. British Nuclear Fuels Limited uses a technique called the Integrated Dry Route, in which uranium hexafluoride vapor and steam react at one end of a rotary kiln to produce uranyl fluoride. The uranyl fluoride is then converted to UO_2 powder in the main body of

Table 1. Depleted UF_6 Management Program options and suboptions being analyzed.

Transportation module		Conversion module		Use module*		Storage module		Disposal module	
Option	**Suboptions**	**Option**	**Suboptions**	**Option**	**Suboptions**	**Option**	**Suboptions**	**Option**	**Suboptions**
Preparation	• Overpack	U_3O_8	• Dry process with AHF** by-product • Dry process with HF neutralization	LWR fuel cycle	• Re-enrichment	Above ground	• Building - U_3O_8 - UF_6 - UO_2	Below ground	• Trench - U_3O_8 cemented - U_3O_8 - UO_2 cemented - UO_2
	• Transfer Facility	UO_2	• Dry process with AHF by-product • Dry process with HF neutralization • Wet process with AHF by-product	Advanced reactor fuel cycles	• Breeder and other fast neutron spectrum reactors				• Vault - U_3O_8 cemented - U_3O_8 - UO_2 cemented - UO_2
Highway	• Truck	U	• Batch metallothermic process with AHf by-product	Dense material applications	• Existing applications: munitions, armor, counterweights, and ballasts • New applications	Below ground	• Vault - U_3O_8 - UO_2		• Mined cavity - U_3O_8 cemented - U_3O_8 - UO_2 cemented - UO_2
Rail	• Flatcar		• Continuous metallothermic process with AHF by-product	Radiation shielding	• U-metal shielding for spent nuclear fuel • UO_2 shielding for spent nuclear fuel		• Mined cavity - U_3O_8 - UF_6 - UO_2		

* Shaded areas include option/suboptions considered but not analyzed in depth.

** Anhydrous hydrogen fluoride (HF).

the kiln by a mixture of hydrogen and steam introduced at the opposite end of the kiln. The reaction byproducts are hydrogen fluoride and water.

Mixed Oxide Fuel Application

One use for UO_2 resulting from the conversion of depleted UF_6 is for blending with plutonium dioxide (PuO_2) or highly enriched UO_2 for the production of mixed oxide fuels (MOX) for light water reactors (LWRs). Currently, mixed oxide fuels are used in Europe, where reprocessing of spent LWR fuels yields considerable plutonium and slightly enriched uranium which can be recycled. Japan is also pursuing plutonium recycle and MOX fuels. The materials used (in Western Europe) to fabricate MOX reactor fuels for LWRs are slightly enriched UF_6 and plutonium recovered from spent nuclear fuel (SNF) recycling. The role for depleted uranium in this system would be as feed to a fast breeder reactor (FBR) cycle. Unlike the LWR cycle, the breeder cycle includes two discrete fuel types: a driver fuel, consisting of 20-30% plutonium in DU, and a blanket fuel, consisting of DU only. Although with the slowed growth of nuclear power there is no economic driver for the fast breeder reactors today, several demonstration FBRs were built in Europe in the 1970s, and the French built two large FBRs (Phenix and Super-Phenix).

If depleted uranium were used in the once-through (no SNF recycling) cycle used in the U.S., it would be as a UO_2 blend with weapons uranium or plutonium in place of enriched uranium. When consideration is given to the quantities of depleted uranium used in either the reprocessing cycle or the once-through LWR cycle, it is clearly not cost-effective to utilize depleted uranium in the production of MOX fuel in the U.S.; however, there may be limited application in blankets of sodium-cooled FBRs.

Conversion of depleted UF_6 to uranium dioxide for storage until the time of future application as MOX fuel has the advantage of retaining the uranium in a more stable and inert form. However, the costs of conversion of a substantial quantity of the depleted UF_6 inventory to UO_2 would be lower than conversion to uranium metal. Operation of fast neutron breeder reactors is technically mature, although mixed oxide (UO_2 and PuO_2) fuels can be more economically fabricated by reprocessing spent light water reactor fuel rods. The safe, long-term storage of UO_2 can be achieved, although public acceptance of a breeder reactor program may be forthcoming only after the fossil fuels are nearly exhausted.

DUCRETE Application

The Department of Energy is currently developing a multi-purpose container for use in the future storage, transportation, and disposal of spent nuclear fuel. It has been proposed that UO_2 could be used in concrete as shielding material in these containers. Concrete is generally a mixture of cement, sand (SiO_2), and aggregate (gravel, usually SiO_2 forms). By substituting a uranium oxide in the place of either the sand or the aggregate, a depleted uranium concrete (DUCRETE) can be produced

which has a much higher density than standard concrete. Current DUCRETE development has focused on using stabilized dense UO_2 as the aggregate and U_3O_8 as the substitute material for the sand to achieve the desired density.

A manufacturing site for DUCRETE production would have to handle the oxide source material. The primary health and safety concerns arise from internal radiation exposure due to inhalation of airborne oxides or from the chemical toxicity of the uranium as a heavy metal due to ingestion. Therefore, a concrete factory producing DUCRETE would need to be fully enclosed and equipped with air filtering, pressure control, radiation detection, etc. Disposal of DUCRETE after container use would present additional waste management issues, although this issue may be mitigated in the case of deep geological disposal of spent nuclear fuel. Breaking up large DUCRETE structures would entail airborne particulate hazards similar to those produced during manufacture. The costs for manufacture and disposal of DUCRETE would exceed those of concrete. The technology for large-scale production of DUCRETE has not been developed. Use of DUCRETE as shielding material for on-site storage of spent nuclear fuel or in shipping containers appears to be a reasonable option, although life-cycle costs could be somewhat high, particularly when decontamination and decommissioning costs of such facilities are considered.

Conversion to DU Metal

Depleted uranium metal has been produced for many years, primarily for defense purposes. The standard industrial process in the U.S. has been the batch metallothermic reduction of uranium tetrafluoride with magnesium metal (Ames process). This process generates a magnesium fluoride byproduct slag which is contaminated with appreciable quantities of uranium in various forms. Without further treatment, the slag (about 0.5 kg/kg-U) must be disposed of as low-level waste. There are a variety of options to decontaminate the slag, including options which also recover the fluorine value for recycle.

Another option is continuous metallothermic reduction, which offers higher throughput than the currently practiced batch process, and a MgF_2 byproduct with a much lower level of uranium contamination. A fundamentally different option is the plasma dissociation of UF_6 gas. In the presence of a hydrogen quench, the end products are uranium metal and anhydrous hydrogen fluoride (AHF).

Metal Shielding Application

The beneficial re-use of depleted uranium metal for radiation shielding of commercial SNF or vitrified high-level waste (HLW) containers has been considered by the Office of Technology Development. Uranium provides an effective gamma shield, and depleted uranium metal could be utilized in containers for storage and transportation of vitrified HLW (Yoshimura 1993), in metal shielded casks for on-site dry storage and subsequent shipment of SNF (Hertzler and

Nishimoto 1994), or incorporated in the shield plug for multi-purpose container designs. It was concluded that these applications could possibly use the entire inventory of depleted uranium. This particular application addresses two major concerns: SNF/HLW shielding and depleted uranium disposition.

Conversion of depleted UF_6 to uranium metal has been accomplished for decades by one of several technically mature industrial processes. The conventional Ames reduction process produces an amount of solid waste, mostly in the form of MgF_2, approximately equivalent to that of the uranium metal produced. This solid waste would have to be disposed of as low level waste or else processed to remove nearly all of the uranium in order to dispose of the waste in a sanitary landfill. Use of uranium as shielding for spent fuel rods in various casks designed for storage and transportation requires that the uranium be protected against oxidation during manufacture and storage. Utilization of uranium metal for shielding in SNF and HLW canisters appears to be a viable option for the re-use of the depleted UF_6.

Conversion to Uranium Carbide

Uranium carbides (UC) are usually manufactured in spherical shapes and then assembled into the desired form. To date, most uses for uranium carbide have been in nuclear fuel applications. Depleted UF_6 can be converted to UO_2 by various methods previously described. The UO_2 then becomes the starting material for microsphere production (Bennedict, Pigford, and Levi 1981). In a commonly used process, the UO_2 powder is mixed with carbon flour and an ethylene binder to form a slurry, which is oven-dried and milled to sand-sized particles. The oxides are converted to carbides in a vacuum heating step. Subsequently, coatings are applied to the microspheres in a fluidized bed furnace to isolate the UC from the environment at the microscopic level (GA Technologies 1982). The coated spheres are then assembled into fuel rods for reactor use. In some applications, other types of fuel materials (e.g., thorium) may be incorporated into the fuel with the spheres.

High -Temperature Gas Reactor (HTGR) Fuel Application

The typical commercial HTGR fuel cycle utilizes high enriched (93%) uranium (HEU) and thorium (Th). Potential HTGR fuel cycles using depleted uranium include a low enriched (LEU) cycle, which would use a mixture of 5-15% enriched UO_2 and depleted UO_2, and an HEU cycle, which could be blended down with depleted uranium or recycled U-233 (from a previous HEU-Th cycle). Although there are no commercial HTGRs currently operating in the United States, several have operated in the past, and advanced HTGR design work is underway.

Typical fuel fabrication plant for HTGRs convert UO_2 and thorium dioxide (ThO_2) into fuel elements. The fuel element for an HTGR consists of a hexagonal block of graphite into which vertical coolant and fuel holes are drilled. The fuel holes are filled with rods consisting of a graphite sleeve containing a column of cylindrical fuel compact. In addition to fuel and coolant channels, fuel elements

contain a small amount of boron carbide (BC), formed into rods, to act as a burnable poison. HTGR fuel consists of tiny, spherical, carbon-coated, enriched UC_2 and Th particles blended together and formed into rods by means of a matrix filler and binder. The basic steps in manufacture of HTGR fuel assemblies are: particle production; fuel rod fabrication; and element manufacture. Particle production consists of a fissile particle production process which results in either HEU or LEU uranium carbide fuel particles. The fertile particle production process results in the formation of Th particles or, in the case of a depleted uranium cycle, the formation of depleted uranium fertile fuel particles. The fissile and fertile particles are then fabricated into fuel rods through an injection molding process, and the resulting fuel rods are positioned in their respective channels to form the fuel element.

In order for depleted uranium to be used in the HEU-Th cycle, it must first be heavily re-enriched, which does not prove to be economically feasible. It is more likely that depleted uranium would be consumed through the LEU cycle, with the following assumptions: (1)depleted uranium stockpile is re-enriched to 15% for use in the fissile particle production; (2) the remaining 0.1% tails are used in the fertile particle production in place of the Th; (3)the material weight requirements for the LEU fissile and fertile particle production are the same as in the HEU-Th case. In this scenario, almost 600 metric tons of the depleted UF_6 stockpile could be consumed annually. If the depleted uranium were used in the fertile particle production only, approximately 540 metric tons could be used annually. This use rate assumes a reference facility that produces approximately 96 fuel assemblies per day.

Conversion of depleted UF_6 to uranium carbide requires the initial conversion to UO_2, producing a CaF_2 waste stream and hydrofluoric acid (HF), followed by formation of UC by either a graphite or gelation method. Additional costs arise from the use of depleted, rather than naturally occurring, UF_6 as the feed material, due to the substantially increased energy costs associated with gaseous diffusion. Relatively small quantities of depleted UF_6 would be expected to be utilized by this process due to the lack of commercial acceptability of the HTGR technology. Public acceptance for the construction and operation of additional nuclear power plants in the U.S. has diminished in the last 15 years. Therefore, the option of using significant quantities of depleted UF_6 as HTGR fuel does not appear to be reasonable at this time.

Conversion of UF_6 to U_3O_8

The conversion of UF_6 to U_3O_8 is commonly referred to as defluorination. The by-product of the defluorination process is either HF or anhydrous HF (AHF), depending on the process selected. There is a large market for AHF in North America, but only a limited market for hydrofluoric acid. In Europe, however, there is a large market for concentrated hydrofluoric acid (typically 70% HF). Cogema operates the world's only defluorination facility (France) for depleted UF_6. Two example processes are provided below for the conversion of UF_6 to U_3O_8.

The Cogema process for defluorination with hydrofluoric acid by-product is a two-step, vapor-phase process. In the first step, UF_6 vapor is hydrolyzed with steam (at 250%C) to produce solid UO_2F_2 and gaseous hydrogen fluoride and water. The oxyfluoride is then fed to a rotary reactor and pyrohydrolyzed (at 750%C) with hydrogen and superheated steam to give U_3O_8 and additional hydrogen fluoride gas. The HF/steam stream is filtered and condensed to recover concentrated HF.

In the U.S., General Atomics has developed a process to produce U_3O_8 with an AHF byproduct. This patented process also involves a two-step reaction sequence to produce U_3O_8. UF_6 is first reacted with steam to produce a uranyl fluoride intermediate and a gaseous mixture of HF and water. The second step then converts the intermediate by steam to U_3O_8 and a gaseous mixture of HF, water, and oxygen. The gaseous HF/H_2O mixtures from the two reactors are combined and separated in a distillation column to obtain an AHF stream and an aqueous azeotrope stream. The azeotrope stream is vaporized and recycled to the primary reactor as steam feed. Although this process has been successfully demonstrated at a laboratory scale, it has not yet been commercialized at the industrial scale.

Due to the reactive nature of UF_6, the depleted uranium inventory could be converted to U_3O_8 for interim or long-term storage. The advantages of U_3O_8 are the relatively low chemical reactivity, solubility, and health risks compared to other uranium forms. U_3O_8 is insoluble even in the weak acids and bases typically found in soils and groundwater (Martin Marietta 1990). Storage of the material in the form of U_3O_8 would not preclude the use of this material at a later date.

Conclusion and Discussion

The overwhelming response to the Request for Recommendations and the assessment of the technologies presented in this paper, as well as others, indicate that there are opportunities to utilize the depleted uranium resulting from the enrichment process in the nuclear fuel cycle. Completion of the Technology Assessment Project ended the first phase in the process of selecting a long-term management strategy for the Department's depleted uranium. A more detailed engineering and cost analysis is ongoing. These analyses will be utilized in the development of an Environmental Impact Statement and the final Record of Decision, which is scheduled to occur in 1998.

The Depleted Uranium Hexafluoride Management Program has provided an opportunity for public involvement in a major federal action and engaged private industry in the development of a cost-effective management strategy for disposition of this material. This program actively encouraged the involvement of the public and private sector in the Department's decisionmaking process. The consideration of re-use applications is important as the U.S. and other countries continue to strive toward a sustainable economy and to minimize wastes associated with energy production and other industrial processes. A program such as the one described here could be used as a model for many other issues currently facing the U.S.

Department of Energy and other federal agencies, including the re-use of federal facilities and the disposition of excess government equipment and materials.

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Utilization of Already Separated Plutonium in Russia and International Security Problems: Consideration of Short- and Long-Term Options

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Abstract

Today there are a growing Russia's stocks of separated plutonium, recovered from dismantled nuclear warheads and from military and civil reprocessing plants that present an international security problem. In the long term, the basic Russian approach for disposition of this plutonium is to burn both weapons plutonium and civil plutonium in the fast-neutron reactors, but due to current political and economical situation in Russia this plan can not be realized any time soon. Under such conditions the first priority should be placed on the set up of a plutonium storage regime under bilateral or international control.

Introduction

The plutonium stockpile, created by both nuclear disarmament and civilian nuclear program, presents the serious risk to national and international security. However, the utilization of already separated plutonium, particular of excess plutonium from retired nuclear weapons, is rising a complex set of technical, economical, environmental and political problems. All these problems are closely related and mutually reinforcing. What is the best approach to minimize the risk associated with plutonium stockpiles in Russia is the subject of this paper.

FSU/Russian Stock of Weapons Plutonium

During the cold war the FSU/Russian nuclear military production complex produced about of 125 tons of weapons-grade plutonium.

As the results of nuclear arms reduction most of this plutonium will become "surplus". Currently Russia is dismantling nuclear weapons and plutonium components at rate of some 7 tons per year which are being shipped to storage at the disassembly plants near Seversk (Tomsk-7), Ozersk (Chelyabinsk-65) and Arzamas-16. It is expected that some 100 tonnes of plutonium will be released from weapons in Russia[1] (Table 1).

Furthermore, Russia will continue to produce significant amounts of weapons-grade plutonium. Only 10 of the 13 Russian plutonium-production reactors have been shut down. Although, the three remaining reactors are now operating principally to supply heat to cities Tomsk and Krasnoyarsk, they continue

Table 1. Estimated Weapons Plutonium Production in FSU/Russia by 1995.

Type of reactor	Power, MWt (designed/upgraded)	Period of operation	Estimated WPu production, MT
A	100 / 900	06.19.48 / 06.16.87	6.5
IR-AI	50 / 500	12.22.51 / 05.25.87	3.4
AV-1	300 / 1200	04.01.50 / 12.08.89	8.9
AV-2	300 / 1200	04.06.51 / 06.14.90	9.0
AV-3	300 / 1200	09.15.52 / 11.01.90	6.3
I-1	600 / 1200	11.20.55 / 09.21.90	8.5
I-2	600 / 1200	09. .58 / 12.31.90	8.2
ADE-3	1600 / 1900	07. .61 / 08.14.90	11.9
ADE-4	1600 / 1900	02.26.64 / in operat	12.2
ADE-5	1600 / 1900	06.27.65 / in operat	11.6
AD	1600 / 1800	08.25.58 / 06.30.92	13.5
ADE-1	1600 / 1800	. .61 / 08.29.92	12.3
ADE-2	1600 / 1800	. .63 / in operat	12.7
Total			124.7

to produce weapons-grade plutonium at a rate about 1.5 metric tonnes each year. Last fall the Russian government has obligated that as of October 1, 1994 all newly produced plutonium be not used in weapons and will be stored in the oxide form.

Russian Stock of Civil Plutonium

Table 2 presents the amounts of fuels discharged from Russian power reactors[2] and estimates of the amounts of reactors-grade plutonium.

Table 2. Russian civil plutonium production data.

Reactor's type	Mass of spent fuel, MT	Estimated mass of RPu, MT
RBMK	6100	38
VVER-1000	1000	11
VVER-440	1250	17
BN-600	65	6
Total		72

Russia is reprocessing spent fuel from domestic and Soviet-built reactors VVER-440, BN-600 power reactors, naval reactors, and research reactors. At present, about 30 tons of separated reactor-grade plutonium[3] in the form of the plutonium dioxide is being stored at Chelyabinsk-65. It is supposed to fabricate this material into reactor fuel before beginning to use weapons plutonium because the growth of the radioactivity in the civilian plutonium due to decay of Pu241 makes it difficult to handle.

Russian Approach for Plutonium Disposition

The Russian Ministry of Atomic Energy (MinAtom) views plutonium as a valuable energy sources.[1] It's concept, of how to utilize plutonium, is based on that approach which was developed two decades ago when there was a great energy demand, and entails the following two measures:

1) storage of both surplus weapons and civil plutonium;

2) fabrication of MOX fuel for future use in a different types of reactor: fast-neutron reactors and light-water reactors.

In the past in Russia, use of plutonium in thermal reactors was viewed to be ineffective. For this reason all existing Russian LWR reactors (VVER-440, VVER-1000) were not designed for use of MOX fuel although some Russian experts believe that four modern VVER-1000 units at the Bolakovskaya NPP could be modified and loaded with MOX (1/3 core). If so, each of these four reactors would utilized 250 kg plutonium annually. Currently MinAtom in collaboration with France, Germany and the U.S. is conducting technical and economical evaluation of plutonium utilization in commercial LWRs. But experts from the GosAtomNadzor (Russian Nuclear Regulation Agency) and from Institute of Physics and Power Engineering in Obninsk expressed their doubts[11] that even modern VVER-1000 reactors can be easily modified at moderate cost and licensed to accept plutonium fuel. Due to lack of experience in fabrication and use of MOX fuel in a light water reactors, it is rather questionable whether Russia can realize this option soon.

The utilization of plutonium as MOX fuel in fast reactors looks more attractive.[4] Russia has the experience in production and use the plutonium fuel in the BOR-60, BN-350 and BN-600 fast reactors. The new BN-800 fast reactor is designed and has passed all required examinations. No problems are expected with plutonium of various isotopic compositions. Also, the fast-neutron reactors could process larger amounts of plutonium than LWRs of equal power output, and the radiotoxicity of its spent fuel would be significantly less.

To implement this concept of plutonium utilization, MinAtom proposes to build four 800-Megawatt fast-neutron reactors: three near Chelyabinsk-65 and one at Beloyarskaya site and to complete the construction of "Shop-300" MOX plant at Ozersk site. Additionally, MinAtom argues that implementation of this plan will

diminish risk of diversion and thefts because fuel fabrication, fuel and plutonium transportation will be within a closed site. The estimated cost for this project is about of $3.8 billion: $800 million to complete construction of one BN-800 ($765 million[5]) and "Shop-300" plant ($35 million[2]), and $3 billion for construction three additional BN-800s.

A research and development program was adopted by MinAtom to coordinate efforts on implementation of technology and construction of equipment to use of weapons plutonium in the MOX-fuel fabrication for fast and thermal reactors. This program includes:

- processing of metal plutonium to plutonium oxide in the procedures of its dissolving, filtration, purification, precipitation and heating;
- fabricating of the fuel elements and fuel assembly;
- processing of the radioactive wastes resulted from the conversion procedure;
- production of the containers for secure and safety storage of plutonium dioxide and for it transportation;
- construction of storage facility.

MinAtom requested $8.5 million as a part of the FY 1995 funds to support this program, but up to June, 30, 1995 it has received less than 10 % of these planned funds.[6] This fact illustrates that given Russia's current chaotic political and economical conditions, it seems unlikely that plans on plutonium utilization will be carried out any time soon.

As for non-reactor options, there is currently little enthusiasm in MinAtom for this approach to plutonium disposition. Use of the existing vitrification technology has always been perceived as unsafe.[10] Another reason for the lack of enthusiasm is that phosphate-based glass produced for vitrification of the high-level radioactive waste at reprocessing plant near Chelyabinsk does not appear as durable or have sufficient safety advantages.

Another possibility for the disposition of Russian plutonium is to use it for MOX fuel fabrication and sell this fuel on the word market. MinAtom proposed such sales to the U.S., Japan and Canada. Although the U.S. and Japan are not interested in these proposals, the Canadian government as well as Canadian nuclear industry has expressed support to this proposal. Preliminary investigations about such sales for Canadian CANDU reactors are currently in progress.

Prospect for Plutonium Use in Russia

Although Russia has some experience with fast-neutron reactors, and the fabrication of plutonium fuel, the future of Russian nuclear industry in next several

decades will not be associated with plutonium due to several factors. These factors are:

- The production capabilities of the Russian uranium fuel fabrication complex allow support of the nuclear power industry with a total capacity of 100 GWt.[7] The currently installed capacity is 22 GWt.

- Russia has a huge stocks of HEU and uranium tails which are estimated to be 1200 MT and 300,000 MT respectively.[9] As a result of nuclear arms reduction most of the HEU will became excess and can be use for nuclear fuel production, which in turn results in cheap fuel.

- The total Russian enrichment capacity is about of 15 million SWU/y.[7] Enrichment plants based on the advanced centrifuge technology can provide enriched uranium fuel at prices substantially below those existing in the world uranium market.[8] Evidently, Russia can support the operation of both domestic and Soviet-built nuclear power reactors in others countries for a decade without mining new uranium ore. (See Table 3).

It is clear that currently there is no economical motivation for Russia's nuclear industry either to reprocess spent fuel or to use plutonium for fuel fabrication. The reprocessing activity at "Mayak" is carried out to earn hard currency from the contracts with Finland and Hungary. This gives "Mayak" a chance to survive in the current economic environment in Russia. Without these contracts the operation of RT-1 plant would be completely unprofitable. As for the use of plutonium, taking into account that Russia has an over capacity for production of low-cost LWR fuel, it will be difficult for MinAtom to justify and get a large-scale subsidy to implement its preferred disposition concept. This factor, and the new Russian legislation now being developed which establishes stronger environmental standards and regulations for the operation of the nuclear industry, will result in the delay of plutonium use for a substantial period of time.

Table 3. An estimate of natural uranium and SWU needs for domestic/Soviet-built type reactors.

Reactor's type	Number	Enrichment	Amount of fuel, MT	SWU, million	Natural uranium, MT
RBMK	11/15	2.4	418/570	1.05/1.43	1965/2680
VVER-1000	7/18	4.0	168/432	0.9/2.33	1344/3456
VVER-440	6/22	3,5	64/233	0.3/1.07	452/1645
BN-350/600	1/2	20	6/10	0.24/0.4	258/430
ADE	3		3600		3600
Total				2.49/5.23	7619/11811

Conclusion

These observations indicate that the real question that needs to be answered is what priority needs to be placed on short-, medium-, and long-term to identify and choose between different disposition options. This question is easily answered when one considers the current turbulent political and economic situation in Russia. The priority that makes the most sense is to concentrate efforts on short-term options. The main concern, and highest priority for now, must be to create a regime that will prevent the reuse of weapons grade material in new weapons and prevent diversion to the black market. This will create a base for irreversibility of nuclear-weapons reductions and confidence in the international community that no proliferation of nuclear weapons is taking place. There is no other objective that could command a higher priority.

It seems there is only one way to realize this goal. That is to make a determined effort to set up a reciprocal regime of storage of plutonium under bilateral or international control.

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Future of the Reprocessing Business at the RT-1 Plant

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Abstract

The economic viability of reprocessing operations at the RT-1 plant is provided today by contracts with nuclear utilities from Finland and Hungary. However, Finland plans to stop sending fuel to Mayak for reprocessing after 1996; and Hungary will be able to provide interim storage of spent fuel domestically by in 1996. These developments make uncertain the future of the Mayak's reprocessing business.

Introduction

The Production Association Mayak in Chelyabinsk-65 (in the past Combine 817 in Chelyabinsk-40) was established in 1948 as an integrated complex to support the production and maintenance of nuclear weapons. Defense activities remain an important mission of Mayak. The complex produces tritium and tritium warhead components, stores and processes fissile materials, fabricates HEU and plutonium components of nuclear warheads, and plays a role in the fuel cycle of naval propulsion reactors. In the 1970s, Mayak also began commercial activities, including the production of radioisotopes, the management of spent fuel from commercial power reactors, and the production of machinery and instrumentation.

In 1991 Mayak became independent from the state budget financially and currently has to be viable economically. This proved difficult. The freefall of the Russian economy and nuclear disarmament have drastically reduced defense orders. Moreover, because of the economic crisis, the central government often does not pay in full to facilities of the warhead production complex even for products and services which have been produced under the state orders. Under these circumstances, reprocessing of foreign spent fuel has become the principal source of revenues for Mayak. These revenues, however, cannot be assured in the future because the foreign contracts are a subject to political uncertainties. The loss of the foreign contracts would likely undermine Mayak's reprocessing business.

RT-1 Reprocessing Plant

The radiochemical plant RT-1 (Plant 235), built on the site of the first military plutonium separation facility (Plant B), was brought into operation in 1976. Its first processing line was designed to reprocess HEU uranium-aluminum fuels of naval reactors. In 1978, the plant began reprocessing fuel of VVER-440 reactors. At

present, the RT-1 plant processes fuels of VVER-440, BN-350/600, naval, HEU-fueled, and research reactors. The plant has three chopping-dissolution processing lines:

- The VVER-440 line has a name-plate capacity of 400 MTHM/y and a historic average throughput of 200 MTHM/y.[1] But recently, the line has been operating at 25-30 percent of its capacity.

- The naval reactor line processes HEU uranium-aluminum fuels of naval reactors. The line's potential capacity is approximately 10 MTHM/y (20-30 reactor cores per year).[2]

- The HEU-fuel line processes irradiated 90-percent enriched spike rods of the remaining plutonium production reactors and driver fuel of the Mayak's tritium production reactors. Recently, the facility has been processing several hundreds kgHM fuel per year.

At later stages of the technological process, there is a possibility of manipulation and merger of the streams of materials from each of the three processing lines. Plutonium, recovered from irradiated fuel, is converted to oxide and placed in storage. Approximately 30 MT plutonium oxide was accumulated at the RT-1 plant by 1995. Reprocessed uranium is blended with natural and highly-enriched uranium and is recycled in power and plutonium production reactors. In the past, uranium recovered from irradiated HEU fuel of the plutonium and tritium production reactors was recycled in naval propulsion reactors.

In addition to the radiochemical processing lines, the RT-1 complex includes pools for interim storage of spent fuel, waste management facilities (including a HLW vitrification facility), and MOX fuel research and production facilities. The RT-1 plant is supported by other Mayak's units, such as the Central Research Laboratory, Instrument Engineering Plant, Repair and Machining Plant, and South Ural construction unit. As of 1992, the RT-1 plant employed approximately 2500 people.[3]

Reprocessing of Naval and HEU Fuel

As of 1995 the Navy and the commercial icebreaker fleet had approximately 120 reactor cores of spent fuel stored at coastal facilities and on service ships. Defueling of the retired submarines will increase the amount of spent fuel to 300-350 reactor cores.[4] Many additional cores will be discharged as a result of on-going operational activities of the Navy and icebreakers.

The existing backlog of spent fuel and submarine dismantlement will provide enough work to the naval fuel processing line for tens of years, even if it operates at 100 percent capacity. (At present, the processing rate is largely limited by the rate of shipments of spent fuel from naval bases to RT-1. Seven shipments, each carrying

2.5 cores of spent fuel is planned for 1995.) This work, however, does not add to plant's revenues.[5] The Navy is facing considerable difficulties in finding money to pay for reprocessing. As of June 1995, the cost of sending two reactor cores to Mayak for storage and reprocessing was eight billion rubles (equivalent to approximately $1.8 million).[6] This fee was hardly enough to cover the cost of production.

The rate of reprocessing of HEU fuel from the material production reactors has significantly dropped due to the shutdown of 10 out of the 13 plutonium production reactors. Also, this work is funded by Minatom and currently has only negative value for Mayak. As a result Mayak recently has been refusing to reprocess fuel from the reactors in Tomsk-7 and Krasnoyarsk-26 still in operation.

Reprocessing of VVER-440 Fuel

There are 27 operating VVER-440 reactors worldwide, and a few more could be brought into operation in the future (Table 1). Assuming that each reactor generates approximately 12.5 MTHM/y of spent fuel, the total amount of spent fuel generated every year is over 300 MTHM. In addition, 6.2 and 7.4 MT is discharged annually from the reactors BN-600 and BN-350. These amounts, however, do not automatically translate into expensive reprocessing contracts for Mayak.

- **Russia.** The four units of the Kola- and two units of the Novovoronezh nuclear power plants generate approximately 75 MTHM/y. However, whether Mayak is paid for reprocessing of this spent fuel is not known. As of January 1995, Rosenergoatom, the nuclear utility organization of Minatom, had a debt of 1.45 trillion rubles (approximately $350 million).[7] A significant fraction of this debt was owed by fuel cycle facilities.

- **Ukraine.** In 1994, the four VVER-440 units of the Rovno nuclear power plant experienced difficulties because of the saturation of the at-reactor spent fuel storage facilities. The problem has been resolved by a government-backed reprocessing contract between the Rovno plant and Mayak.[8] However, because of the economic difficulties in Ukraine, the contract is likely to be of low economic value for Mayak.

- **Bulgaria.** In the past, Bulgaria had a standard spent-fuel-back agreement with the USSR. This agreement is no longer valid and spent fuel has been accumulating at the Kozloduy site. Reportedly, recently Russia has agreed to accept and reprocess spent fuel from Kozloduy's VVER-440 units.[9] Financial aspects of this arrangement are not known. But given economic difficulties in Bulgaria the deal is unlikely to be very profitable for Mayak.

- **Finland.** Reprocessing arrangements between the Finnish utility Imatran Voima Oy (IVO) and Minatom are covered by a reprocessing contract, dating back to the agreement between IVO and the USSR regarding the operation of the two Loviisa's VVER-440 units. The contract has no time

limits but has to be renegotiated every five years. The last shipment from Loviisa to Russia (7 casks with 216 fuel assemblies containing approximately 26 MTHM spent fuel) took place in the fall of 1993.[10] The reprocessing of Finnish fuel has provided a significant source of revenue. However, the Finnish Ministry of Trade and Industry has prepared legislation that would ban shipments of spent fuel to Mayak after 1996 because of safety and environmental concerns. (There are also speculations that IVO is not completely satisfied with its reprocessing fees.) IVO plans to expand its interim storage facility and has initiated a study to find a spent fuel repository site.

– **Hungary.** On 1 April 1994, Hungary and Russia signed a protocol regarding the return of spent fuel to Russia from the four units of the Paks nuclear power plant.[11] The first shipment under the new contract, approximately 60 MTHM of spent fuel, took place in January 1995.[12] Paks, with its current backlog of approximately 400 MTHM and annual generation of approximately 50 MTHM of spent fuel, may remain a significant customer of Mayak in the future.

  Reportedly, reprocessing fee for a single shipment of spent fuel (55 MTHM) from the Paks nuclear power plant in Hungary is "over $10 million", corresponding to $200 per kgHM. Other sources suggest, however, that the reprocessing fee is 700-800 per kgHM.[13] Mayak gets less than 40 percent of these payments. According to the presidential degree, 25 percent of these revenues are collected by the Administration of the Chelyabinsk region. (Presumably, the funds are allocated towards environmental clean- up and improvements of the social infrastructure in the region or in the city of Chelyabinsk-65 (Ozersk).) One half of the remains is withheld as a tax by the state. The RT-1's gross profit can be estimated at $4-15 million per year. RT-1's operation and maintenance costs are not known, but, because the plant is fully amortized, they are expected to be relatively low. (Foreign contract revenues are also used to cover the cost of reprocessing of domestic spent fuel.) RT-1's net profits probably do not exceed ten million dollars. They, however, might be essential for the survival of the RT-1.

  It appears that Hungary would like to take full use of the protocol and to continue sending fuel to Mayak. However, Hungary is also constructing an interim dry storage facility and investigating potential final repository sites.[14] Because the Paks output represents half of the electricity generation in Hungary, the decision was made to assure that "no situation could arise which would threaten this power supply".[15] In addition, the plant's managers believe that an interim storage provides Hungary with "independence and cost control over what is an essential part of our economy".

The facility is designed to hold fuel from ten years of the plant's operation but can be extended to accommodate spent fuel corresponding to 30 years of reactor operation (1,875 MTHM). The construction work is well underway, and the facility is expected to be ready to accept the first fuel shipments in 1996.[16]

- **Czech Republic.** In December 1994, the governments of Russia and Czechia signed a nuclear cooperation agreement allowing spent fuel from the Dukhovany nuclear power plant to be sent for reprocessing to Russia. However, in 1992 the republic decided to forgo reprocessing and to construct an interim storage facility to keep fuel for 50-70 years. A year-long trial operation of the Dukhovany facility is expected to begin in the fall of 1995.[17] The decision was taken on economic grounds and is unlikely to be affected by the new agreement.[18]

- **Slovak Republic.** All fuel from the Bohunice nuclear power plant was shipped to Russia prior to 1989 under the agreement between former Czechoslovakia and the USSR. Most fuel currently stored at Bohunice is from the Czech's plant at Dukhovany and it will be returned to Czechia.[19] The Slovak republic does not have a reprocessing agreement with Russia.[20]

  The Slovak government also intends to complete two VVER-440 units at Mochovce (currently 75 and 90 percent complete). Whether spent fuel would be reprocessed or not is not known.

- **New clients?** Potentially, Mayak could hope for reprocessing contracts from new clients. In October 1995, Armenia restarted one unit of the Metzamor plant, two reactors of which were shut down in 1989 in the aftermath of a disastrous earthquake.[21] Also, a recent agreement between Minatom and Iran envisages construction of a two VVER-440 unit nuclear plant in Iran and related fuel services. Whether these plans will be implemented and whether this would result in reprocessing contracts is highly uncertain.

Conclusions

Theoretically, spent fuel from naval propulsion and VVER-440 reactors will provide enough work for the RT-1 plant in the future. RT-1's domestic customers presently do not have any alternative to reprocessing. Foreign utilities which are operating VVER-440 reactors (with the exception of IVO of Finland) will likely keep their reprocessing arrangements as long as they are provided with convenient fuel cycle packages (including fabrication of low-cost fresh fuel) and as long as reprocessing fees stay low.

However, the future of the RT-1's reprocessing business might be very fragile. Indeed, the bulk of its present revenues is generated by the services to utilities from Finland and Hungary. To a significant extent, these hard currency revenues help Mayak to service its domestic customers. After 1996, however, Finland will stop sending spent fuel to Mayak. Hungary is constructing an interim spent fuel storage facility and, should the arrangements with the RT-1 change, will be able to manage spent fuel domestically. (Such a change could be triggered, for example, by Russia's new law, according to which foreign radioactive waste must be returned to the country of origin.)

Notes

1. Between 1978 and 194, the plant reprocessed 2,380 MTHM.
2. During the last ten years, the Navy shipped on average 16 cores of spent naval fuel per year. Between 1973 and 1995, the RT- 1 plant received and reprocessed approximately 300 reactor cores of spent fuel. (V.Kurnosov and V.Perovsky "On Upgrading the System of Spent Fuel Management at Russian Navy's Sites", presented at NATO workshop on submarine decommissioning, Moscow, June 1995.)
3. T.Cochran, S.Norris and O.Bukharin *Making the Russian Bomb: From Stalin to Yeltsin*, Westview Press, 1995, p. 84.
4. Of 126 submarines retired by March 1995, spent fuel was removed from only one third. Additional 40-80 submarines are expected to be removed from the service by the end of this decade. (O.Bukharin, J.Handler "Russian Nuclear-Powered Submarine Decommissioning", *Science and Global Security*, 1995, Volume 5, pp. 245-271.
5. The principal likely benefit of the reprocessing of naval fuel for RT-1 is that it allows the plant to maintain the production and employment.
6. V.Kurnosov and V.Perovsky "On Upgrading the System of Spent Fuel Management at Russian Navy's Sites", presented at NATO workshop on submarine decommissioning, Moscow, June 1995. Assuming the exchange rate of $1 = 4,500. A part of the cost is a transportation fee which is paid upfront to the Ministry of Railways. The other part is presumably paid to Minatom for reprocessing. The reprocessing fee is paid in several installments, stretched over the period of several months. It is believed that Minatom has had difficulties in collecting the money. (Communication with Russian officials, January-June 1995.)
7. Rosenergoatom itself was owed more than 1.6 trillion ruble ($400 million). (*Nucleonics Week*, 26 January 1995.)
8. *Nuclear Fuel*, 27 September 1993.
9. *Uranium Institute News Brief*, 95/14 (29 March - 4 April, 1995).
10. This was the 13th spent fuel shipment. A total of 2,343 fuel assemblies (279 MT) has been sent to Russia. Additional 1231 fuel assemblies remain in the interim storage pool at Loviisa; of them, 480 (57 MTHM) will be sent to Russia for reprocessing in 1995-96. (*Nuclear Engineering International*, February 1995.)

11. The original agreement, signed 28 December 1966, covered only delivery of fresh fuel.
12. 480 fuel assemblies were returned on 18 January 1995; additional 3200 fuel assemblies remain in storage at Paks. (*Nuclear Fuel*, 30 January 1995.)
13. Nuclear Fuel, 30 January 1995. According to Minatom statements, Hungary pays to Russia $40 million per year. (*Nuclear Fuel*, 9 May 1994.) This corresponds to reprocessing fees of 800 per kgHM.
14. The facility will be constructed at Paks the using modular dry store technology developed by GEC-Asthom. On 4 February 1995, Hungary's National Atomic Energy Commission issued a license for the construction of the storage facility. However, in an agreement with the local government, the Paks NPP Ltd. guaranteed that no spent fuel will be placed at the store unless Russia refuses to accept fuel. (*Nuclear Fuel*, 13 February 1995.)
15. "Construction gets underway on Hungary's Modular Vault Dry Sore", *Nuclear Engineering International*, June 1995, pp. 16-19.
16. The facility will be built in three phases and will have a capacity of 4,950 fuel assemblies (approximately 620 MTHM). The first phase will have a capacity of 1350 fuel assemblies (approximately 170 MTHM). Ibid., p. 16.
17. *Uranium Institute News Briefing*, 95/37 (period 6-12 September 1995). Fuel will be stored in Castor-type storage and transport casks.
18. Reportedly, Czech nuclear utility CEZ has expressed interest in temporary storage of fuel in Russia. (*Uranium Institute news Briefing*, 95/38 (period 13-19 September 1995).)
19. The first shipment of spent fuel was returned from Bohunice to Dukhovany in the summer of 1995. (*Uranium Institute News Briefing*, 95/31 (period 26 July - 1 August 1995).)
20. There is an agreement to send to Russia fuel from the 120 MW Bohunice-1A reactor (currently shutdown). (*Nucleonics Week*, 25 August 1994.)
21. Loading of fresh fuel in Metzamor Unit-2 was continuing in August 1995. (*Uranium Institute News Briefing*, 95/35 (period 23-29 August 1995).)

Part III

"Effective Elimination" of Weapon Plutonium, and "Elimination" of TRU

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Abstract

For a nominal quantity of 50 tons of excess weapon Pu, to go beyond the Spent Fuel Standard to the "Effective Elimination" level in LWRs would require more than two recycle stages, taking 24 RY of full-core MOX operation beyond the spent fuel standard and costing some $1.32 B more. To actually "Eliminate" the 50 MT of excess W-Pu in a series of MOX-burning fast reactors might be achieved with 303 MWe reactors by consuming all the W-Pu in a first phase of 40 years of operation of 7 reactors, followed by some 7 burn-down stages of 13.5 years each, resulting in a residue of some 4.4 MT of TRU (for a total of 135 years). Neither of these interpretations of going "beyond the spent fuel standard" makes economic, environmental, or non-proliferation sense in the context of a continuing nuclear power economy.

Introduction

In 1992 the Committee on International Security and Arms Control (CISAC) of the U.S. National Academy of Sciences began the study that would lead in January 1994 to the publication of its Report "Management and Disposition of Excess Weapons Plutonium."[1] This work was supported by the U.S. Department of Energy, but the study was done by the entirely independent individuals constituting the continuing CISAC committee of the NAS.

The CISAC Pu Report considered what might be done to limit the threat of reuse or diversion of excess weapon uranium and weapon plutonium—at least 50 tons of W-Pu scheduled to emerge by the year 2003 from the excess weapon inventory of the former Soviet Union, and also from that of the U.S. There is clearly resource value associated with excess high-enriched uranium,[2] and that resource value is not significantly diminished by blending down the HEU (typically >90% U-235) to a U-235 content below 20%. At this level, the material cannot be used to make a nuclear explosive with a reasonable amount of metal, although it (like the 4% U-235 that constitutes the typical LEU fuel for LWR) would allow enrichment to HEU with substantially less investment than if one needed to start with natural uranium. The HEU question was not addressed in the plutonium study because the solution to the specific nuclear proliferation problem posed by HEU is already known and, in principle, a U.S.-Russia contract is already in place to solve it for 500 MT of Russian HEU—by diluting it to LEU fuel stock.

For W-Pu (typically 94% Pu-239, 6% Pu-240), no such simple solution exists, although there is at least ten times as much reactor plutonium ("R-Pu") as soon-to-be-excess W-Pu in the world. Most of this R-Pu is present in the form of spent fuel in cooling ponds at reactors or elsewhere, and in order to use it to degrade W-Pu to some degree, the fuel would need to be reprocessed. The CISAC Report emphasizes, though, that R-Pu itself can be used to make powerful nuclear explosives, without requiring more sophistication than is needed to use W-Pu. In fact, the same designs as those for the early Pu weapons would yield at least one or two kilotons (KT) of energy release,[3] and the Report states on the basis of classified studies done for CISAC, that much higher yields could confidently be expected from more specialized configurations. Thus the degrading or denaturing of W-Pu with R-Pu would increase the proliferation hazard by making available additional separated Pu.

For the disposition of excess W-Pu, the CISAC recommendation is to store the material securely and safely until it can be converted to a form that is less accessible for diversion or theft. Even after the W-Pu has been converted to this less accessible form, it will still need to be stored safely and securely, but the time required to make a nuclear weapon after theft or diversion would be significantly[4] longer than in the case of theft of the intact core of a nuclear weapon ("the pit") or of W-Pu stored as ingots or oxide. Nevertheless, the degree of "conversion" mandated for this purpose is moderated by the recognition of the weapon utility of R-Pu in spent fuel from civil reactors.

In order to have a specific goal for its analyses, CISAC adopted the aim of making excess W-Pu no more attractive for a bomb maker than would be a comparable amount of R-Pu. Thus, CISAC adopted the "Spent Fuel Standard" for evaluating the desirability of various candidate approaches to the treatment of W-Pu.

As is well known, CISAC strongly recommended two approaches for disposition of surplus W-Pu in the U.S., and they were evaluated also for disposition of excess Russian plutonium. The first approach is the vitrification of W-Pu with the high-level wastes,[5] in a vitrification plant under construction in any case at the Savannah River site. In this way, about 1% Pu by weight would be incorporated in borosilicate glass logs each weighing about 2000 kg and containing on the order of 400 kg of high-level fission product wastes. The ratio of Pu to fission products in this material would be much less than that typical of spent LWR fuel, although the Pu, if recovered, would be 94% fissile Pu rather than the 70% fissile Pu typical of civil Pu.

The second approach recommended by CISAC is the fabrication of W-Pu into MOX fuel for existing LWRs (or for CANDU) reactors, with a W-Pu content typically 4-7%, with the purpose of burning this fuel to normal burnup levels of, say, 40 MWD/kg of fuel. Under these circumstances, the spent fuel will contain several percent Pu-239, but will be of a quality similar to that from normal LWR spent fuel. For instance, a 1200 MWe PWR could load 1672 kg per year of Pu (94% fissile) and

download 1174 kg/yr of Pu (76% fissile) to be compared with a normal PWR fueled with 3.8% LEU, downloading 253 kg/yr of Pu (70% fissile).

It is important to recognize that CISAC recommended that both the vitrification and the MOX options proceed through the hardware stage, as if each was going to be adopted as the baseline disposition program, in order to minimize the time that will elapse before actual disposition, and also to gain the benefit of competition.

The Pu study recognized that either disposal option in the United States would have an additional cost on the order of $1000 million (within a factor 2 more or less), assuming the 50 tons of excess W-Pu metal to be provided free of charge.[6] Although the W-Pu has the same energy value as U-235, the fabrication of MOX fuel is so much more expensive than the fabrication of LEU fuel that (even with free W-Pu) MOX fuel costs more than paying all the costs for obtaining uranium, enriching it, converting, and fabricating LEU fuel. I assume here that the cost of fabricating MOX fuel is $1600/kgHM, given free W-Pu oxide, and the purchase cost of LEU fuel rods is $1400/kgHM.

The CISAC Panel on Reactor Related Options considered in more detail the several specific options for partially burning W-Pu in various types of reactors, in a once-through approach, together with the vitrification option, and published its detailed and lengthy analysis July, 1995.[7]

I continue to believe that the "Spent Fuel Standard" for availability of excess weapon Pu is an appropriate one.

As previously emphasized, after the excess weapons Pu has been transformed into spent fuel or its equivalent, the overall proliferation hazard could then be reduced most effectively by efforts to minimize the accessibility of the most accessible spent fuel, rather than by further elimination or sequestering of the specific "spent fuel" to which the W-Pu has been converted.

Of course, if reactors could eliminate the W-Pu entirely at little additional cost rather than bringing the W-Pu just to the spent-fuel standard, we would welcome that achievement. Thus, at this point we look in some detail at what would be involved in going "beyond the Spent Fuel Standard" toward the elimination of the relatively small residual risk posed by excess W-Pu, when it has been converted to the equivalent of additional spent fuel.[8]

Two Approaches to "Elimination"

We address two senses in which weapons plutonium can be 'eliminated', and the ways in which reactors could be used to 'eliminate' it—"elimination of added risk" or "Effective Elimination" on the one hand, and "total destruction." It is not

recommended to go beyond the Spent Fuel Standard, but these results illustrate what would be involved in doing so.

The present paper is an abbreviated version of a 22-page Resource Paper available through CISAC[9] of which some copies are provided for distribution at the Global '95 Conference. For simplicity, I consider eliminating even the "residual added risk" from the weapon plutonium in the context of a continuing nuclear economy. The typical once-through burning of W-MOX in a PWR (for instance) will leave about 70% of the initial Pu in the spent fuel. Specifically, a 1200 MWe PWR fueled with 6.8% MOX discharges annually approximately 1174 kg Pu per year, of which some 889 kg is fissile. Had this PWR been fueled with LEU, it would have discharged about 253 kg Pu per year, of which 177 kg is fissile. Thus the use of a normal PWR without recycle for disposition of excess W-Pu increases the world stock of R-Pu (present in spent fuel rods in pool storage, in dry casks, and eventually in a mined geological repository), so that from an initial stock of 50 tons of W-Pu, 27 tons of Pu will exist in these forms in excess of that which would have been transferred if the PWR had operated on LEU. The W-Pu has not been totally eliminated, although the special proliferation risk posed by the separated W-Pu has been judged to be largely eliminated by meeting the Spent Fuel Standard.

The problem of safeguarding excess Pu is in no way comparable with that of safeguarding a stock of valuable material like gold. The owner of $1000 million of gold can consider various levels of security in order to protect the gold against theft. Presumably increasing the amount spent on such security will reduce the likelihood of theft. It would be reasonable to spend $1 million on security in order to reduce the likelihood of theft to 0.1% and the expected loss (in case of total theft) to the same $1 million. More precisely, the optimum amount to be spent on security is that for which the marginal benefit (reduction of expected loss) is equal to the increase in marginal cost for additional security.

There are no great social costs associated with the theft of a small amount of the "gold". With Pu, however, the matter is quite different. Considering a nominal 4 kg of W-Pu per nuclear weapon, theft of an entire stock of 50 MT of excess W-Pu would suffice to make some 12,000 nuclear weapons. World security would already be sufficiently imperiled by the illicit production of 10-100 nuclear weapons that we are concerned to eliminate the prospect of theft of even that much material—i.e., 0.1% to 1% of the total. Because of the cost of fabrication of Pu-bearing fuel, W-Pu is worth less as nuclear fuel than is U-235; the value of U-235 is set as some $24/g by the U.S.-Russia contract to deliver 500 MT of HEU (blended to LEU) for $12 B.

So a 4-kg Pu core for a nuclear weapon is worth less than $100,000 on the energy market (much less—even less than zero), but since a single nuclear weapon can kill more than 100,000 people and cause much more than $100 B worth of damage, the "externalities" can be a million times larger than the value of the material. For gold, damage to society in case of loss is comparable with the price of the material, not one million times as large.

Thus the problem is more a qualitative one than a quantitative one. There is so much R-Pu in the world that there is no prospect that all or even a large fraction of it will be stolen or otherwise diverted and processed into nuclear weapons. The concern is to prevent even some small multiple of 10 kg (ten parts per million of the world stock of 1000 MT of R-Pu) from being stolen and processed into nuclear weapons. For this reason, adding 27 MT to the large existing stocks of R-Pu in the United States or in Russia does not add significantly to the proliferation risk. A thief wanting to divert spent fuel would go after the older and less radioactive material, or the material which is least well guarded.

"Effective Elimination" of Weapon Pu

Nevertheless, as an intellectual exercise, it is of interest to see how this additional R-Pu can be eliminated or avoided by the investment of additional funds. For this purpose, we consider recycle of spent fuel derived from the W-Pu, and indeed multiple recycle until the additional R-Pu is reduced to zero. This means, of course, that the stock of Pu left over from the necessary number of reactor years should be not zero but just the same as that of the reference reactor operating on LEU. "Beyond . . ."[10] shows that recycle is necessary for any reactor loaded with WPu-MOX that discharges more than P = 253 kg/y of Pu annually. The concept is shown in Figure 1 which shows on the lower curve the tons of R-Pu produced from the reference reactor, while the top line is the stock of Pu in the presence of an ELWR[11] like the system 80+. In this case, the total elimination of added risk occurs after 66.56 RY of operation.

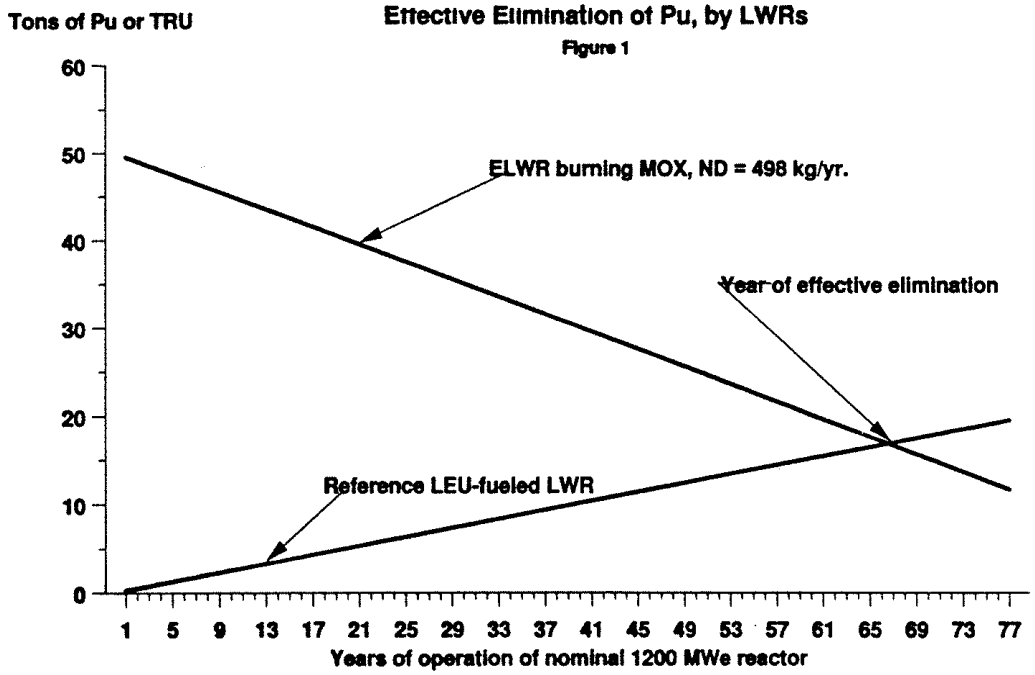

Fig. 1. Effective elimination of Pu, by LWRs.

At this time, the same number of kWh of electricity will have been produced, the same number of tons of fission products, and the residual Pu (more accurately, TRU) will be the same from either approach. This residue is dubbed the Effective Elimination Residue or EER, and in the case of Figure 1 amounts to some 16.84 MT of TRU. This chart and these numbers assume for simplicity that successive recycles have the same reactivity as the initial core of 6.8% W-MOX (appropriately poisoned at beginning of life). This assumption is removed in other examples in Table 1 of "Beyond . . .", such as an ELWR in which the successive TRU fraction in the MOX is 6.8%, 9.76%, 11.6%, and 15.85%, keeping the reactivity approximately constant in a thermal spectrum.

In this (still approximate) calculation, 24.25 RY of full-core MOX operation beyond the 29.90 RY that can be fueled with W-Pu MOX without reprocessing (and the steady supply of 24.80 MT of MOX per RY) are required to bring the total stock of TRW to that which would have existed without the injection of the 50 MT of W-Pu. The EER in this case is most readily calculated as the R-Pu generated by the reference PWR (that downloads 253 kg of Pu per year) as (24.25+29.90)*0.253 = 13.70 MT of TRU.

The additional cost associated with this "effective elimination of added risk" is substantial. It is composed of the cost of additional MOX fabrication with highly radioactive recycle Pu, as well as the cost of reprocessing reactor cores in order to obtain this recycle Pu. For comparison, the cost of reaching the Spent Fuel Standard in a once-through process is largely that of conversion of metallic Pu to oxide, and the fabrication of the W-MOX fuel rods. Even so, the best available figures show that the cost of fabrication with cost-free PuO2 exceeds the total cost of purchasing LEU fuel rods. Assuming that the cost of fabrication of recycle Pu MOX is the same as that for virgin W-Pu MOX, and amounts to some $1600/kgHM (compared with a cost of acquisition of fabricated LEU at $1400/kgHM), additional fabrication costs total some $120 M beyond the Spent Fuel Standard and above the cost of LEU fuel. Reprocessing charges (at $1000/kg of fuel) total some $1196 M.

Thus one could expect to pay on the order of $1316 M to reduce to zero the W-Pu contribution to the world stock of R-Pu.

I emphasize that I think it is entirely unnecessary and economically undesirable to spend $1.32 billion to avoid the 27-ton R-Pu residue from the 50 MT of W-Pu in the once-through fuel cycle. The additional funds are better spent on providing better security for the existing spent fuel that is least well protected.

It is also true that Pu in the inventory can be reduced in other ways that have nothing to do with recycle of the irradiated MOX resulting from the W-Pu. Additional improvements in efficiency of the world's nuclear reactors would do it, as would the transition to other types of reactors. But if these steps are worth taking to compensate the addition of 27 MT of R-Pu residue from 50 MT of W-Pu, they are worth taking without the addition of the W-Pu.

Nevertheless, the number ($1.32 billion, with associated uncertainty) speaks for itself as an example of the additional cost required for "effective elimination" of Pu by LWRs, constituting the elimination of added risk from the residual Pu.

Of course, there is additional risk involved in the recycle operations, the cost of which has been taken into account here, but not the potential for accident or leakage, which are (I hope properly) assumed to be negligible during these operations in the United States, Europe, or Russia.

"Beyond . . ." considers other reactor systems for effective elimination, such as an LWR burning sterile oxide (SOX), which instead of requiring some 54 reactor years, would require some 39 RY. Still, the problem of qualifying a SOX fuel in a normal commercial reactor is not trivial, and such an approach cannot be recommended.

Naturally, effective elimination could be achieved also with a fast-spectrum metal-cooled reactor, such as the ALMR considered in the United States, and the number of RY required depends on the conversion ratio for the reactor. Assuming the conservative CR = 0.67 described by contractors in their submission to the DOE Plutonium Disposition Study (PDS), some 90 years of operation of a 1200 MWe cluster of ALMRs would be required for effective elimination. If these reactors could burn sterile fuel, only 43 years of operation would be necessary.

"True" Elimination of W-PU and the Resulting TRU

The other approach to "Elimination" of the W-Pu would be to continue recycle until "all" of the Pu and any resulting TRU had been consumed. Clearly, this will take even longer and cost more than simply to reduce the residual TRU to the level that would have been produced by a set of reference reactors operating for the same time (that is, producing the same number of kWh, as in the Effective Elimination analysis), but it costs very little to estimate how this might be achieved and what the cost would be.

Furthermore, it would make no sense to reduce to zero some particular contribution of TRU in an ongoing nuclear power economy.

Thus I have considered the option of plutonium elimination in a declining or absent nuclear power economy. The task, then, would be not to eliminate TRU from 50 MT of W-Pu, but to consider the elimination of a much larger amount of TRU left over from a nuclear power economy. We have considered a stock of 2000 MT of TRU, and (for simplicity) burning it in fast reactors, so that successive stages of recycle are assumed to be not very different from the first stage.

We could then consider a small slice of this operation for the destruction of the 50 MT of excess W-Pu.

As will be seen, there are two stages to annihilation—a first "burn-down" stage in which a ton of fissile material is burned to fission products per gigawatt-year of electric energy production in almost any type of reactor, and a major parameter is the "conversion ratio" in a reactor that uses mixed-oxide fuel containing fertile U-238; and a second "burn-out" stage in which less than a reactor-load of Pu is burned in an exponential decay driven by a neutron flux provided by the fission of U-235. Alternatively, spallation neutrons for the burn-out stage can be provided by use of a high-energy, high-power proton beam.

The duration of the first stage depends primarily on the number of reactors provided with W-Pu fuel (some 50 GWe-years for 50 MT of W-Pu, with non-fertile fuel) and to some extent on the reprocessing delay, which might result in a 7-year delay[12] after a typical 4 years fuel residence time in the reactor.

One important point is the division into two phases, as above, the "burndown phase" and the "burnout phase", distinguished by whether there is more or less than a reactor core of Pu. Beyond that, there is the interesting point that in the exponential "ultimate burnout phase" of the sub-core residue of Pu, no reprocessing is necessary if the pins have been fabricated with a burnable poison to have small net reactivity.

Figure 2 shows TRU stock vs. time for a population of small (303 MWe) advanced liquid metal reactors (ALMR).

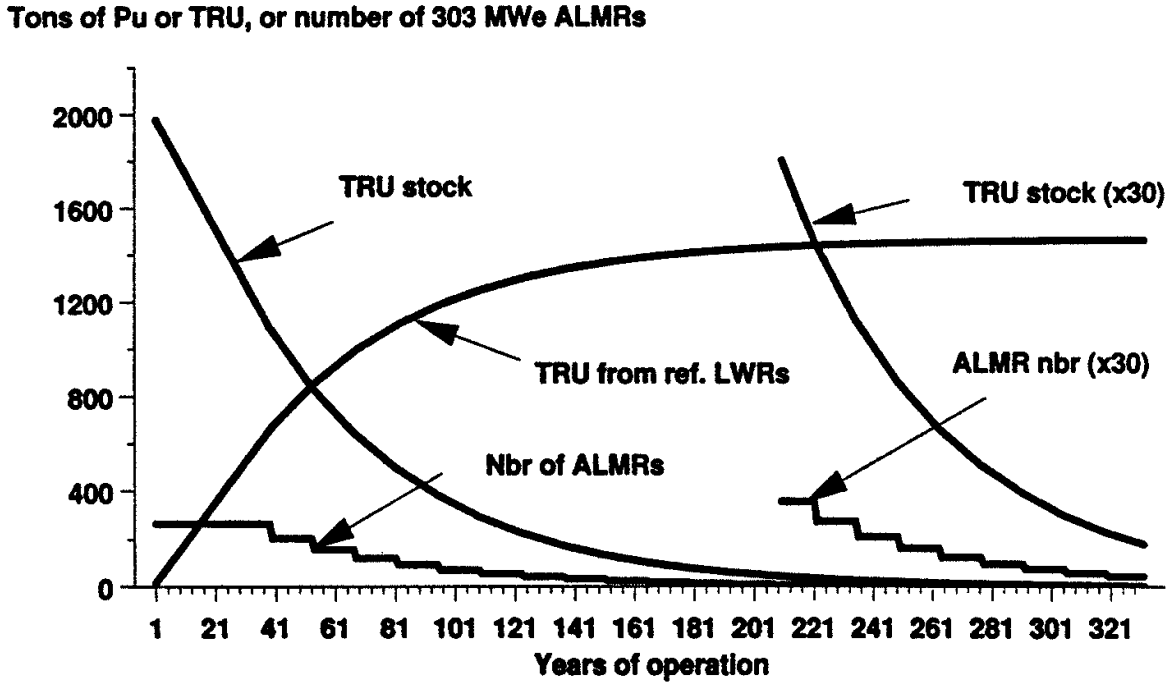

Fig. 2. TRU elimination by ALMR burning MOX.

This is a typical 303 MWe solid-fuel sodium cooled fast reactor which consists of a driver section only, with steel reflector and a conversion ratio CR of 67%. Four such reactors provide 1200 MWe at an efficiency of 36%, producing 924 kg of fission products annually. The net destruction of TRU is 305 kg/yr per 1200 MWe. The TRU fraction of fresh fuel is 20.2%; annual fueling rate is 6.48 MTHM/yr for a TRU fueling rate of 1309 kg/yr, and the TRU output is 1004 kg/yr after 6.5 years fuel residence time in the reactor.

For the total elimination approach,[13] in the steady state, each 303 MWe reactor contains about 2.40 MT of TRU and is fed 0.368 MT for seven years, which is the assumed YD delay in availability of recycle fuel from reprocessing. After seven years, the feed of exogenous fuel drops to the net annual consumption of 76 kg/yr per reactor. Assuming that number of ALMR are to be deployed to burn all the initial Pu stock as MOX in 40 years, (and available recycle TRU), after which the number of operating reactors will need to be reduced by a factor r, the ratio of actinide mass per kg of spent fuel to that of fresh fuel. In this example r = 0.769.

In addition to YD = 7 years of unprocessed spent fuel from each operating reactor, the inventory of a terminated reactor will fuel a continuing reactor for 6.5 years, so the duration of a step is 13.5 years. For an assumed initial stock of 2000 MT of TRU, 21.2 reduction steps (following 40 years of initial operation of 267 small reactors) will require 327 years to reduce to the inventory of a single ALMR of about 4.4 MT. Incidentally, for an initial stock S and a fraction lost to waste in each reprocessing step of e, the overall actinides lost to waste amount to $S \times e \times r/(1-r) =$ 6 MT, for e=0.1%.

To dispose of 50 MT of excess W-Pu beginning with a 40-year operation of a fleet of small ALMRs, seven such fast reactors would be required. The second, stepped burn-down phase would then occupy some seven periods of 13.5 years each, ending with a single exhausted reactor core[14] in a total of 135 years. About 165 kg of TRU would have gone to the waste stream, primarily in the earlier years of the process, assuming a loss to waste of 0.1% per cycle. To this point small ALMRs would have operated for some 545 RY, and at a feed of 1.84 MT/RY this would have required 1002 MT of MOX, of which 980 MT would have been reprocessed. Assuming (without justification) \$1600/kgHM for fabrication of this 20.2% fuel, and \$1000/kgHM for reprocessing this high-TRU fuel, fuel-related costs (without final disposal) amount to \$2612 million for the production of 165 GW-yr of power. The 137 RY of 1200 MWe LWR operation that could have produced the same energy would have consumed 137×24.8 MT of LEU, which at \$1400/kgHM would have cost \$4774 million. It is not surprising to find the ALMR fuel cycle cost less than that of the LWR[15]—a difference that would be nullified if the non-fuel (capital plus operating) cost of an ALMR exceeded that of a 1200 MWe LWR by \$15 M per year.

To eliminate the residual TRU which is too small in mass to be critical in the ALMR-size reactor, "Beyond . . ." then considers miniature reactors with larger TRU fractions operating at some 400 kWt/kg TRU, providing a near-exponential

reduction in residual TRU with a decay constant of the order of 13-25 years. This could provide a reduction in TRU stock to some 40-100 kg in some 30-60 years (plus the 165 kg already considered as having gone to waste).

Any further burnout would require spallation neutrons from an accelerator or from a HEU driver.

Of course, the required time for these reductions could be reduced by the use of reactor designs with higher specific power density (MWt/kgTRU) and by reduced reprocessing time. This brief paper treats reactors that have traditionally been considered for the supply of electrical power.

Conclusions

For a nominal quantity of 50 tons of excess weapon Pu, to go beyond the Spent Fuel Standard to the "Effective Elimination" level in LWRs would require more than two recycle stages, taking 24 RY of full-core MOX operation beyond the spent fuel standard and costing some $1.32 B more.

To actually "Eliminate" the 50 MT of excess W-Pu in a series of MOX-burning fast reactors might be achieved with 303 MWe reactors by consuming all the W-Pu in a first phase of 40 years of operation of 7 reactors, followed by some 7 burn-down stages of 13.5 years each, resulting in a residue of some 4.4 MT of TRU (for a total of 135 years). Neither of these interpretations of going "beyond the spent fuel standard" makes economic, environmental, or non-proliferation sense in the context of a continuing nuclear power economy.

References

1. *Management and Disposition of Excess Weapons Plutonium*, Report of the National Academy of Sciences, Committee on International Security and Arms Control. (National Academy Press, Washington, DC 1994).
2. That energy resource could readily be exploited in an LWR, for instance.
3. (And, statistically, often much more.)
4. In the sense that there could be significantly more prospect of police action or of response from the international community.
5. (Remaining from the production of the military Pu.)
6. However, the conversion of Pu metal to Pu oxide is assumed to cost $7 per gram, or $350 million, and this is a substantial portion of the cost.
7. John P. Holdren, John F. Ahearne, Robert J. Budnitz, Richard L. Garwin, Michael M. May, Thomas H. Pigford, and John J. Taylor, *Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options*, Report of the National Academy of Sciences, Committee on International Security and Arms Control, Panel on Reactor-Related Options for Disposition of Excess Weapons Plutonium (National Academy Press, Washington, DC 1995).

8. It is worth noting that if the vitrification option and the once-through MOX spent-fuel approach are both accepted as meeting the Spent Fuel Standard, then "elimination of added risk"—EAR—could be achieved by increasing the burnup of LEU fuel in other reactors of the population, increasing the thermal efficiency of the non-nuclear part of the power plant, or the like.
9. R.L. Garwin, "Beyond the 'Spent Fuel Standard': Two Interpretations of 'Elimination' of Excess Weapons Plutonium," (Draft 3 of 08/26/95) A Resource Paper (In process). In preparing that paper and also the current report I have benefited greatly from discussions with Thomas H. Pigford, John P. Holdren, and Jor-shan Choi, as well as from the work of the STATS Panel of the U.S. National Research Council.
10. I will refer to Reference 9 as "Beyond . . ." The final version of 09/06/95 was deposited with the Committee on International Security and Arms Control of the National Academy of Sciences 09/07/95 and is available from them or from the author.
11. Evolutionary LWR.
12. There is nothing magic about 7 years. If there were substantial economic benefits to reprocessing the more highly radioactive fission products after one year, one might achieve a 3-yr delay from removal of the spent fuel to loading of reprocessed and refabricated fuel. And a fluid-fuel system might have a reprocessing delay of a week or less.
13. Incidentally, for the "effective elimination" task, a 1200 MWe cluster would require about 90 years, for an EER residue of 22.67 MT of TRU containing about 15% non-fissile Pu.
14. (Containing about 2400 kg TRU, plus 7 years of unprocessed fuel including some 1980 kg TRU, for a total of 4.4 MT TRU.)
15. (To within the very poor accuracy of this assessment.)

Using Existing European MOX Fabrication Plants for the Disposal of Plutonium from Dismantled Warheads*

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The Problem

For the first time after the end of the Cold War, a substantial reduction of the nuclear arsenals of the U.S. and Russia has been agreed upon in the START treaties. Until 2003, both sides plan to reduce their arsenals from more than 50,000 to 7,000 nuclear warheads. A large part is expected to be dismantled, releasing hundreds of tons of highly enriched uranium (HEU) and plutonium. This creates new concerns: It must be prevented that even tiny fractions of this huge amount of weapon grade material be diverted by unauthorized groups, such as a potentially well organized Mafia which could transfer it into the hands of states with nuclear ambitions or even terrorists. Another danger would arise if Russia's democratic development would not remain stable. In such a case, a new dictator such as Shirinovski could reuse the material rather easily. Generally the opinion prevails that a solution should have a short time scale. A long time storage is considered not sufficient by many politicians and experts. The amount of Russia's excess weapons plutonium is estimated of about 100 tons. The U.S. National Academy of Sciences has released two studies which study disposition options in great detail.[1]

A comparatively simple solution exists for the weapon grade uranium that consists of over 90% U-235: dilution with natural or depleted uranium that exists in abundance will result in low enriched uranium that cannot be used in nuclear weapons any more but in light water reactors. For this reason, the well-known deal for the purchase of Russian HEU by the U.S. has been agreed, its implementation still pending because financial difficulties still have to be cleared.

A similarly simple solution does not exist for plutonium, since all isotopic compositions of plutonium that can be fabricated from existing materials can be used for nuclear explosives.[2] The National Academy of Sciences has defined the so-called "spent fuel standard" for the choice of disposition options: options for the long term disposition should make the plutonium roughly as inaccessible as the plutonium in civilian spent fuel. It then recommends two options that both serve this standard:

- fabrication and use as mixed oxide (MOX) fuel, without reprocessing, in existing or modified nuclear reactors, or

* An earlier version of this paper was presented at the Pugwash Conference in Hiroshima.

- vitrification in combination with high-level radioactive waste (HLW).

The reasons for this choice are especially that these options meet the spent fuel standard and that they are technically advanced enough to be realized in foreseeable time so that the time during which the material is stored in weapons usable form can be minimized. Long term storage is not recommended because the long term political development in Russia can't be foreseen and because wrong policy signals are sent out.

The American energy policy has refrained from plutonium recycling at the time of the Carter administration. For this reason, no MOX fabrication exists in the U.S. and no practical experience with burning MOX in light water reactors. Because of perceived proliferation dangers, the U.S. even have the principle of foreign policy not to support or to encourage technologies abroad that are elements of a closed fuel cycle. However, it is likely that they will build a MOX fabrication factory exclusively for the purpose of nuclear disarmament.

The Russian civilian nuclear policy is completely different. The Russians perceive the plutonium as a valuable energy source which they would prefer to use in fast breeders. But they lack the financial means for implementation of this goal. They reject the vitrification option completely, but they would also be interested in MOX technology because their goal is to set up a civilian closed fuel cycle including technical services such as reprocessing and final waste disposal for foreign customers. So far, also the Russians have no experience with MOX in light water reactors.

The ``Hanau-Option''

Building a MOX fabrication factory in Russia would have the disadvantage of lacking U.S. acceptance, because it is likely that it would trigger a civilian nuclear fuel cycle which would result in even more production of separated plutonium. The European facilities (existing and under construction in France, Belgium, the U.K. and Germany) are already devoted to civilian plutonium and have no free capacity. The only exception is the almost completed factory at Hanau (Germany), which has recently been abandoned by the owner Siemens due to lacking domestic acceptance. If this facility would be used for the Russian plutonium, several obstacles have to be faced, but it has also several advantages. Since minimizing the dangers to international security posed by separated plutonium is also in the German interest, there is the desire to assist with international efforts of disarmament and disposition.[3] The fuel would then be burned in light water reactors in Germany or other foreign light water or CANDU reactors.

Table 1 gives an overview on the situation of MOX licenses for German pressurized water reactors.[4]

The table reveals that the maximum amount of plutonium that the German reactors would be able to consume would be in sum about 50 t, provided that they would be operated until the end of their lifetimes which is rather unlikely. This is not sufficient. Building new reactors is impossible at the time being due to lack of public acceptance. There are additional boiling water reactors which have not been licensed for MOX because of lack of sufficient amounts of plutonium. In principle it would be possible to license these reactors.

Table 1. Overview on the situation of MOX licenses of German pressurized water reactors and maximum of Pu consumption.

Plant	Stage of license	Max. aver. content of Pu-fiss in U-nat (weight %)	Number of MOX fuel elements per reloading	No. of MOX fuel elements in the core	% of MOX fuel elements in the core	Max. rest operating time	Average discharge (tons/ year)	Total Pu consump. until end of lifetime
Brockdorf	issued, operated	equiv. of 4.0 U-235	—*	—*	—*	21	32	—
Emsland	issued	3.8	16	48	25	23	34	5
Grafenrheinfeld	issued, operated	3.07	16	64	33	16	29	4.6
Grohnde	issued, operated	3.2	16	64	33	19	27	5.4
Isar 2	issued	equiv. of 4.0 U-235	24	96	50	23	28	13
Neckarwestheim 1	issued, operated	3.04	—	16	9	11	17	0.5
Neckarwestheim 2	issued	3.8	—	72	37	24	30	10
Obrigheim	issued, operated	3.8	8	28	26	3	30	0.8
Philippsburg 2	issued, operated	3.5	—	72	37	19	28	5.2
Unterweser	issued, operated	3.28	16	48	25	13	28	3.5
Biblis A	applied for	equiv. of 3.5 U-235	24	80	42	9	28	3.7
Biblis B	applied for	equiv. of 3.5 U-235	24	80	42	11	28	4.5
Mühlheim - Kärlich	contested, operation unlikely	—	24	84	39	21	22	—

* According to the amount of self generated Pu.

Table 2 gives an overview.

Table 2. Overview on German boiling water reactors (without MOX license).

Plant	power /MWe (gross)	(net)	starting year
KWW Würgassen	670	640	1975
KKB Brunsbüttel	806	771	1976
KKP-1 Phlippsburg	900	864	1980
KKI-1 Isar	907	879	1979
KKK Krümmel	1316	1260	1984
KRB B Grundremmingen	1300	1240	1984
KRB C Grundremmingen	1308	1248	1985

The addition of these reactors would not be sufficient either. Another possibility would be to make additional use of foreign reactors. The option of using Canadian Candu reactors is also under discussion. These reactors are fueled with natural uranium that contains 0.72% U-235. If it would be replaced by MOX, a rough estimate is that this MOX would contain about 0.5% Pu due to rests of U-235. Canada's annual consumption is about 1,900 tons natural uranium. It is said that a 100% MOX load of Candus would be possible. Consequently, an annual consumption of about 9.5 tons plutonium would be possible.

The Hanau option has several advantages and disadvantages and a complicated background which will be discussed in the following.

Background: The Transition of German Energy Policy

Since several decades, experiences have been gained with the recycling of plutonium covering a wide range of different fuel composition. After a period when the priority of Pu recycling was primarily focused on the goal of fast breeders, the emphasis shifted towards MOX use in LWRs.

The first German experiences with the use of MOX in boiling water reactors (BWRs) have been made in 1966 with the experimental nuclear reactor in Kahl (VAK), in pressurized water reactors (PWRs) in 1972, when MOX use started in the nuclear reactor Obrigheim (KWO). Until 1980, practical experiences have been collected with design, neutron physics of operation, and fuel irradiation. Since 1981, MOX fuel has been used in additional PWRs. In sum, about 6.5 t Pu corresponding to more than 100,000 fuel rods have been processed. Loading has been limited to one third core, although licenses exist up to 50%. So far, no practical experiences

and no licenses exist for full MOX cores. Licensing of existing reactors for full MOX cores would not be possible according to legal requirements.

Until recently, the Atomic Act of the Federal Republic Germany required the reprocessing of irradiated fuel elements and its recycling into a closed fuel cycle. In May 1994, the Atomic Act has been amended. Now it allows also direct geological disposal of spent fuel elements as an equally possible disposition option. Since there is no final disposal site licensed prior to the year 2010, the new freedom results in the choice of interim storage. The background of the nuclear political decisions until the amendment was the requirement of a closed fuel cycle by the Atomic Act.

As there was not enough German reprocessing or storage capacities, the German energy suppliers who must demonstrate six years of forward planning for spent fuel arisings, had to conclude reprocessing contracts in 1978 with Cogema first (covering 1990-2000) and several years later with BNFL (covering 1995-2005). These contracts, also called Base Load Customer Contracts, require that the utilities finance construction and operation on a cost plus fee basis and that they take back their corresponding quantities of Pu, reprocessed uranium and wastes. They foresee the reprocessing of roughly 4,500 t of spent fuel. Much of the spent fuel covered has already been delivered and part of it already reprocessed. In 1988-89, follow-on contracts have been signed. They foresee additional 3,000 t.

After the amendments of the Atomic Act, German utilities began canceling their post-2000 reprocessing contracts because of the perception that reprocessing would be more costly than direct disposal. As a result of the cancellations of contracts, Cogema offered new contracts that foresee intermediate storage and delay the decision of the disposition of the spent fuel. Final decisions have not yet been completed, since they are also affected by the prospects for a geological disposal site at Gorleben, which are also uncertain because of political local opposition. But it is likely that the use of MOX fuel in German LWRs and the demand for MOX fuel fabrication will decrease or even phase out.

A MOX fuel fabrication facility exists at Hanau, owned and operated by the company Siemens AG, formerly by Alkem GmbH, that is 95% completed. It has a capacity of 120 t/year. It was scheduled for a start up in 1993 which did not occur because the local state government, a coalition of antinuclear Social Democrats and Greens, is determined not to have the facility started and makes use of its implementing authority in this way. Federal law is superior of state law, and therefore the Federal Environment Minister can order the State Environment Minister to issue licenses which has happened. Several court rulings were additionally necessary to grant the licenses. But although the new plant is now in possession of all necessary licenses, their implementation had been continuously delayed. Because of delays, costs of court cases and maintenances, and of uncertainty of future demands for MOX fuel, the owner has decided to abandon the facility in June 1995.

In these circumstances it might theoretically be possible to use the facility for disarmament purposes.

Discussion of the Advantages and Disadvantages

Proliferation Risks

The plant has a sophisticated safeguards system that has been developed together with scientists from LANL and that is in accordance to Euratom and IAEA requirements. The plant has one entry and one exit opening. At several points, the total flow of material passes and can be measured independently from each other where it is being controlled by the safeguards authorities. In order to appease international concern, it would not be recommended to operate the plant only by Germans, rather an international framework should be created that provides a maximum of transparency and control. This framework should at least include Russians, Americans, and Euratom.

In contrast to Germany, there are no international safeguards in Russia and much lower standards of material protection, control, and accountancy. Negotiations between the U.S. and Russia with the goal of enhancing the transparency of the disarmament process are under way, but a soon achievement of international safeguards or involving the IAEA is rather unlikely. Russia has no central material accountancy system. The German material accountancy is run by Euratom. There is no additional national system.

Although the U.S. policy is not to encourage closed fuel cycles abroad, this applies even more on a civilian technology of MOX technology to Russia. The closed fuel cycle in Germany is about to phase out anyway. If civilian plutonium is to be replaced by military plutonium exclusively for the purpose of disarmament, this effect would be even accelerated. It is also recommendable to implement a second amendment of the Atomic law which would prescribe the abandoning of reprocessing as disposition option.

The transports might be considered as a proliferation risk. A scenario might be transporting a mastermix of 30% plutonium and 70% uranium oxides via the Baltic sea. This would avoid crossing several East and Central European countries. The mastermix could be fabricated at Russian reprocessing plants. The immediate proliferation risk of transporting directly militarily usable plutonium would be avoided. In Germany, the further transport could take place by rail, as is already happening since years. In case the whole option is not accepted by the population which is likely, the transports might face severe problems by local protesters.

Costs

Russia believes in a positive economic value of their weapon plutonium. Without an economic benefit, Russian acceptance can not be expected.

The German energy suppliers have declared that they would not accept any more additional costs, e.g. a higher price for their fuel than would be ordinary uranium fuel. They have also declared that technically they can run both sorts of fuels and would also accept further MOX, provided there would be no additional costs.

The original costs of the plant have been DM 750 mio. Because of maintenance costs during the last years, costs have now accumulated to DM 1.1 billions. At the time being, running costs are 10 mio./month. Additional DM 250 mio would be needed for a start up which could occur within two years. Decommissioning after a running period of about 20-25 years would cost 550 mio. If it is assumed that depreciation costs do not exist because Siemens would abandon the plant anyway, and if it is assumed that the plutonium would be freely available, additional costs would arise only from running the plant and from transports. Without interest rates, this is estimated to DM 2115 per kg. The equivalent price of uranium fuel must take into account the purchase of natural uranium, conversion and enrichment, and fuel fabrication. According to estimates, this sums up to DM 2500 per kg, so that in this scenario, the difference between the MOX fuel from Russian weapons plutonium and ordinary uranium fuel would be almost DM 400 per kg. This could be paid as net profit to Russia while at the same time the German utilities would pay the same price as for uranium fuel, provided that it would be used in German reactors.

This scenario is a rough estimate which probably has to be worked out in more detail. Some additional costs must perhaps also be taken into consideration: it might happen that the international community might wish additional security of transports. Yet it must be kept in mind that investment in disarmament efforts will be necessary anyway.

Acceptance

The option would only be feasible if there would be international and domestic acceptance. The first requirement is Russian acceptance. As discussed above, economic aspects will play an important role in the Russian decision making, but it must not be excluded that other factors might also be important. For instance, the Russian weapons plutonium is an important symbol of Russia's status as a nuclear power, and it might cause bad feelings if this material is being transferred just to Germany, who was once an enemy and defeated, but is now in a much better economic shape than Russia. An important aspect is also reciprocity. Russia might perhaps not want to start with disposition activities earlier than the U.S. But the time scale in the U.S. will be longer since no facility is available so far.

The second, and indispensable requirement is the consent of the EU and the cooperation of Euratom. This might pose problems because the option runs counter the interests of the French and British reprocessors.[5] Also the consent of the United States as a third requirement is necessary. Discussions in the U.S. administration

take place, and although it seems there is much sympathy, opponents might argue that this would be an encouragement of a closed fuel cycle.

The domestic acceptance is a much bigger problem. The majority of the German population is antinuclear and wants to phase out nuclear energy. The red-green state government of Hesse is determined not to let the Hanau plant operate. Especially the Greens draw part of their identity from the antinuclear stance so that not many changes can be expected from them. On the other hand, the other part of their identity stems from the goal of nuclear disarmament. When the discussion of the option arouse in the public in April, some immediate reflexes of rejection could be observed, such as press articles and interviews. For instance, on May 31, the Hessian Parliament voted for a statement rejecting the idea and calling it "absurd and dangerous''. The reasoning included the following arguments:

- Disarmament is only a pretext, the true reason behind is the survival of the atomic industry.
- The consequence of having the reactors running for several more decades cannot be tolerated.
- It would not be the fastest method because of the limited number of reactors, glassification would be faster.
- Transport is too dangerous.
- Weapon plutonium in Hanau is not licensed, the risks are not investigated.
- Glassification would be the fastest. Russian and American weapon plutonium must be submitted to international control and safekeeping immediately.

Meanwhile all democratic parties have started a more thorough review process by studying the various aspects and inviting experts. Yet even if there would be the rather unlikely event that all democratic parties agree to the option, the public acceptance would probably be still low. In case the Hessian government is persuaded, it must be expected that it will insist on a complete stop of any further civilian reprocessing. This would be a direct contradiction to French and British commercial interests, and might reduce the likelihood of a European consensus. Yet the Europeans must be aware that this might happen even without making use of the Hanau facility.

Time Scales

In theory, the time scale could be the fastest of all options that are in a review process at the time being. Any new construction of a plant would not be necessary,

in contrast to the construction of a new plant in Russia, whose time scale bears a lot of uncertainties. The MOX production could start within two or three years. With a plutonium consumption rate of about 5 tons per year, it would take 20 years to process the estimated 100 tons of Russian excess weapons plutonium. When the burning in reactors starts in parallel, it would in sum take about 25 years until the weapon grade plutonium is converted into spent fuel.

The vitrification option still needs some more research although it is clear that it will be feasible. But further investigation is necessary for the addition of plutonium which still lacks practical experience. Apart from this, financing of the vitrification option poses much more problems.

In practice, the time scale of the Hanau option might be delayed a lot because of the lacking acceptance. Some relicensing would probably be necessary because of the different composition of the Russian weapons plutonium. The existing licenses cover only an isotopic composition with a maximum content of 95% Pu-235. Relicensing procedures offer the opportunity to citizens to challenge it at court which might substantially delay the start. An alternative that would avoid relicensing would be adding some reactor grade plutonium while fabricating the master mix in Russia. But this might be a contradiction to the exclusive goal of disarmament but not of commercial business.

The previous experience also shows that the cooperation of the State Government is an indispensable prerequisite. It is not recommendable to force the implementation of the option through against the State Government. If its acceptance might be gained is highly questionable.

Conclusions

Even if the Hanau option would be used, it would require at least 20 years. It is much more likely that for a long time to come nothing will happen. Therefore a safe and secure storage must be given a high priority in any case. It must withstand attacks and accidents and has to meet high standards of security, accountancy, containment, and surveillance.[6] In Germany and in Europe exist long time experiences of plutonium storage with national physical protection and international accountancy and safeguards. This offers a broad range of collaboration possibilities and should be given a high priority independently from any implementation of disposition options.

Acceptance

The Option would only be feasible if it would attain international and domestic acceptance. The first prerequisite would be Russian acceptance, which depends decisively on economic parameters. There are however, other factors which must also be taken into consideration: Russian plutonium is an important status symbol for Russia's position as a superpower. The very idea of processing in

Germany could stir up sensitivities. An important aspect for the Russians is above all their goal to set up a civil plutonium economy in their country, and also their corresponding interest in a MOX-technology transfer. A solution that would take place in their own country would therefore be much more attractive than one involving action in another. In early summer 1995 it looked two-sided, as if a process in Germany could possibly be considered by the international community, however a technology transfer seemed most unrealistic. For the Russians the Hanau option seemed at the time to be the only relatively realistic possibility, in which they would at least gain a commercial profit from their Plutonium, and it became obvious that they were definitely interested in this option. If it would have been clear that only this option would have been accepted from the international community and the construction of a MOX facility in Russia had been out of question, then it probably would have been possible to reach an agreement with the Russians. As it became apparent that no further initiatives would come from Bonn, and the Hanau option became a less realistic possibility than a MOX-transfer to Russia, Moscow naturally returned to its previous option and explained that the processing of Russia's plutonium in a foreign country was out of the question.

The second important prerequisite would have been the consent of the EU and the co-operation of Eurotom. This would have also not been a certainty, since the French and British reprocessing plants have a strong interest in the continuance of the plutonium economy in Germany. It had even been feared, that influential circles would have raised a strong opposition against the option, had it have been continued, especially if the a requirement would have been the end of the reprocessing as an option for waste management. On the side of the French it was already declared that they would be interested in co-operation, under the condition that French interests wouldn't be endangered.

The third prerequisite would have been the compliance of the United States. The Hanau option was discussed by the U.S. administration and was met with a good deal of sympathy. A few opponents feared that this option would have strengthened the civil plutonium industry. The decision-making process was discontinued when it became clear that Bonn wouldn't support the option further.

The lack of the most important prerequisite, support from Germany, was the definitive reason for the downfall of this idea.[7] In order for the plan to have been carried out, the co-operation of Hessen's administration in Wiesbaden would have been necessary. The idea to use the facility in Hanau for disarmament presented Wiesbaden with a big problem: the electoral success of the Greens is not least explained by the fact that they declared battle against the nuclear industry, and as a symbol for their opposition to atomic energy they successfully prevented the Hanau facilities from having been put back into operation. This was praised by the population, a large part of which is against atomic energy. On the other hand commitment to nuclear disarmament has always been a part of the Greens' identity. The collision of these two goals was a Catch-22 situation that hadn't been anticipated and would have caused a rather uncomfortable dilemma if the plan had have made

further progress, due to the relative complicated reasons for using the facilities in Hanau, which are not easy to convey. An obvious typical reaction from the population is the question, why we should solve the problem, instead of the Russians themselves, who caused the problems with their nuclear armaments. That the plutonium economy would have more likely been abolished with this option than without it, isn't necessarily clear, without having studied the background more closely. Therefore it is not surprising that, no sooner had the discussion about the Hanau option reached the public, were some immediate panicky reactions observed, e.g. from the press. So, for example, the Hessian Parliament voted for a statement on May 31, in which they labeled the idea "absurd and dangerous". The reasons included the following arguments:

- Disarmament is only a pretext; the true reason for the option is the maintenance of the nuclear industry
- Allowing the reactors to be in operation for a few more decades cannot be tolerated
- It wouldn't be the quickest option; Glassification would be faster
- Transportation is too dangerous
- Weapon plutonium in Hanau is not licensed, and the risks are not investigated
- Russian and American weapon plutonium must be immediately submitted to international control

Similar spontaneous reactions of disapproval also came from the SPD in Bonn. In the following weeks and months it became evident, that the Greens and the SPD restrained themselves and first studied the reasons more closely. Positions that were expressed later to the public were differentiated, and although they were as before without sympathy, their willingness to discuss the loathed topic more thoroughly and honestly was clear. The potentiality that it would have perhaps been possible to negotiate a compromise between all four parties and the Hessen Administration, which under specific requirements would have made co-operation possible, shouldn't be ruled out.

This would have required that someone had taken the initiative to start such negotiations and consensus discussions. This would have been the role of the federal government. Such an initiative failed to appear; the only party that was committed to the Hanau option was the FDP. The reason for the lack of commitment from the CDU is easy to determined: even if the overwhelming consensus of the party were to have been reached, it was rational to expect the disapproval of a large part of the public, and the unpopular measures would have lead to strong protests and opposition, but definitely not to more votes for the party.

The concessions, which would have had to have been made to the antinuclear opposition, would have conflicted with the interests of the French and British reprocessing plants thus most likely causing international disgruntlement.

The efforts towards an energy consensus would have become more complicated, since contradictions would have also risen in this area. Also the direction of the Siemens firm, which already rejected the facility, feared - in contrast to the Siemens' factory committee in Hanau, which was above all interested in the employment positions - that this would lead to more problems than advantages. So almost all parties involved decided to silently sit it out and wait until the unpleasant problem, due to a financial deficiency, took care of itself, and thus they wouldn't be guilty for having destroyed the option. In the mean time the MOX as well as the corresponding necessary plutonium for the German atomic energy reactors will be produced in France, and an end is not foreseeable. Protests have failed to appear thus far.

The only advantage which would have resulted from a federal government's initiative for the Hanau option, would have been a positive contribution to nuclear disarmament, which would have been recognised by some international observers. This was not sufficient motivation.

Conclusion

The Hanau Option collapsed; the former director of the facility is now director of a MOX facility in France that supplies MOX for German atomic reactors. The plutonium economy in Germany will continue, and more civil plutonium for Germany will be produced in France and Great Britain. The plutonium from Russian atomic weapons is stored in Russia, and the introduction of international controls is not foreseen. A waste disposal option for this plutonium is not in sight. The Russians are striving as before to build Fast Breeders and to establish a civil plutonium economy in their country. Probably nothing will happen for many decades. The only realistic possibility is to help the Russians achieve better safety techniques, material control, and accounts of material according to West European standards, and to contribute to a storage facility to at least restrain the immediate danger of illegal disjunction. In addition it is urgent to recommend a commitment to international Safeguards also in nuclear weapons state. In this regard however, even the American enthusiasm isn't particularly great.

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4. Wolf-M. Liebholz (Ed.), *Jahrbuch der Atomwirtschaft 1994* (Yearbook of the Atomic Economy).
5. This aspect is very often neglected by non-European analysts. E.g. a recent disposition proposal suggests to offer U.S. fabricated MOX to European reactors, thereby competing with Cogema and BNFL. It assumes that the European interest is simply using MOX instead of U-fuel and not the commercial interest in reprocessing and the spent fuel disposition. It also neglects that Euratom would be principally protective of European nuclear industry, unless there is a European consensus to abandon this principal for superior interests. See NRDC: Proposal for the Disposition of U.S. Plutonium from Weapons, November 16, 1994.
6. E. Merz, The Challenge: Safeguarded Plutonium Storage, Paper presented at the Pugwash Meeting No. 206, Moscow, February 1995.
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Civil Use of Weapons-Grade Plutonium from Russian Nuclear Weapons: The AIDA/MOX Program

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Introduction

The United States and the USSR and later Russia, have concluded a historical agreement upon a drastic limitation of their nuclear weapons.

For many years, enormous national financial efforts have been made in creating these weapons. However, when real disarmament programs have been initiated, it appeared that their application shall also involve a huge amount of investments, but not to such an extent as for the creation of weapons.

Being today in a delicate economical situation, the Russian Party addressed the USA and other developed countries of the international community, and especially France, with a request of help in this important matter.

Taking into account that the rhythm of nuclear weapons dismantling is scheduled more quickly than the time necessary to any recycling solution or even disposal of plutonium, as well as to the processing of highly enriched uranium, it is primordial to take a decision upon the organization of interim storage of nuclear parts from dismantling.

The United States are now helping Russia in creating storage facilities for those materials.

From 1992 on, having concluded a series of agreements with the Russian Party, the French Party is allocating substantial help in several fields, for which this was asked by the Russian Party.

Among the proposals given by France there were those of a design of a process of weapons-grade plutonium recycling.

A program intitulated AIDA/MOX has been elaborated in the frame of bilateral agreements concerning a joint process design; the application of this program is explained in a paper, the authors of which are N.N Egorov, E.G. Koudriavtsev (Minatom, Russia), X. Ouin and B. Sicard (Ministry of Industry and CEA, France).

I have been asked by the authors to present this paper.

AIDA/MOX Program Objective

The consequences of nuclear arms reductions by the United States and Russia will create very large stockpiles of weapons-grade plutonium (W-Pu) and highly enriched uranium (HEU). For the United States and Russia, this represents over a hundred tons of weapons-grade plutonium alone. What will become of this plutonium? This question and its safety-related aspects are raised by processing and interim storage of the dismantled nuclear warheads.

Several options have been considered by the international scientific community:

(1) interim storage and subsequent disposal of the warheads;

(2) destruction of the plutonium inventory without energy production (vitrification, dilution in the ocean, launching into space, etc.);

(3) use of plutonium as an energy resource (PWR/MOX fuel, fast-neutron reactor fuel, accelerators, new reactor designs).

The solution advanced by France and Russia under the current bilateral cooperation is to use the weapons-grade Russian plutonium in the form of mixed oxide fuel in existing Russian reactors (VVER 1000 and BN 600) and in future reactors (VVER and BN 800). This solution was adopted after considering the relevant criteria, including the energy potential of plutonium, technical and economic factors, long-term radiotoxicity, nonproliferation, the expertise of the Russian nuclear industry, and industrial experience with MOX fuel.

AIDA/MOX Program

The Franco-Russian government-level agreement on the use of Russian weapons plutonium in Russian civil nuclear power plants covers six technical research topics:

Topic 1: Strategies for destruction of weapons-grade nuclear materials (U and Pu).

Topic 2: Feasibility of recycling plutonium as MOX fuel in Russian VVER and BN reactors.

Topic 3: Plutonium chemistry: transformation of metal or alloyed plutonium into sinterable plutonium oxide to fabricate MOX fuel.

Topic 4: Fabrication of MOX fuel for pressurized water reactors and fast-neutron reactors from sinterable weapons-grade plutonium oxide (fabrication processes, plant design, radiological protection, etc.).

Topic 5: Reprocessing of mixed oxide fuel from pressurized water reactors and fast-neutron reactors.

Topic 6: Optimizing reactor designs for the destruction of weapons-grade plutonium.

Current Research Status

The results of the research programs to date may be considered from two standpoints:

(1) The possibilities for using weapons plutonium in existing and future Russian reactors, and the reference scenario for using weapons plutonium in Russia (Topics 1, 2 and 6).

(2) Possible processes for transforming metal or alloyed plutonium into plutonium oxide powder (Topic 3) and then into mixed oxide fuel assemblies for PWRs or fast reactors (Topic 4).

Utilization of Russian Reactors

The results of work carried out jointly by the IPPE Institute in Obninsk by the Kurchatov Institute in Moscow and by the CEA's Nuclear Reactors Division at Cadarache are shown in Table 1. Based on preliminary results that must be confirmed by next year, the quantities of weapons plutonium that can be loaded into Russian reactors are indicated in the table:

- ***Existing reactors***

  - BN 600: approx. 300 kg per year by recycling 24% MOX fuel (hybrid core)

  - VVER 1000: approx. 250 kg per year by recycling 30% MOX fuel (1/3 core)

- ***Future reactors***

  - BN 600: approx. 1310 kg per year by recycling 100% MOX fuel

  - BN 800: approx. 1660 kg per year in a core designed for 100% MOX fuel

  - VVER 1000: approx. 850 kg per year in a core designed for 100% MOX fuel

  - VVER 500: approx. 370 kg per year in a core designed for 100% MOX fuel

These results are now being confirmed by the French and Russian participants, but already they show that the existing Russian reactors could use a significant quantity of weapons plutonium. The joint short-term reference scenario involves simultaneously recycling plutonium in the BN 600 reactor (in a hybrid core) and in four VVER 1000 reactors (Balakovo). In this scenario, 300 + 4 x 250 = 1300 kg of weapons plutonium would be used annually in Russia.

Table 1. Utilization of Russian reactors to recycle weapons-grade plutonium.

Reactor Type	Annual Loading (kg)	Annual Unloading (kg)	Difference (kg)
BN 600 (24% MOX):			
Core	300 (W-Pu)	270	-30
Axial Blanket	0	25	+25
Total	300 (W-Pu)	295	-5
BN 600 (100% MOX):			
Core	1310 (W-Pu)	1195	-115
Axial blanket	0	70	+70
Total	1310 (W-Pu)	1265	-45
BN 800 (100% MOX):			
Core	1660 (W-Pu)	1520	-140
Axial Blanket	0	90	+90
Total	1660 (W-Pu)	1610	-50
VVER 1000:			
Depleted U (1/3 core)	254 (W-Pu)	308	+54
VVER 1000:			
Depleted U (full core)	846.8 (W-Pu)	547.2	-299.6
VVER 1000:			
Natural U (full core)	327.3 (W-Pu)	224.5	-147.8

Transformation of Weapons-Grade Plutonium into MOX Fuel (TOMOX Facility)

All the chemical processes that have been investigated under the Franco-Russian cooperation agreement are shown here (Figure 1). The program seeks to achieve two objectives:

(1) First, to convert the initial denatured military objects into plutonium nitrate, and then into sinterable plutonium oxide powder. The main processes investigated for this purpose from 1993 to the present include:

- HCl (VNIINM, Moscow)

- HNO_3 (VNIINM, Moscow and CEA/Atalante, Marcoule) - Direct oxidation (CEA)

- Pyrometallurgy (RIIAR, Dimitrovgrad).

These processes will be submitted to a comparative review at the end of this year, and a single process will probably be selected for the joint research program scheduled for 1996.

(2) Conversion of the plutonium nitrate into a uranium/plutonium mixture containing 30% Pu. Three processes have been investigated during the last two years:

- Coprecipitation (VNIINM, Moscow)
- Chemical conversion to PuO_2 and powder mixture (CEA)
- Plasma chemical conversion (Khlopin Institute, St. Petersburg).

Here again, the advantages and drawbacks of each process will be compared at the end of 1995, and one of them probably selected for the 1996 joint research program.

A preliminary design study for a TOMOX facility by COGEMA and SGN, at the request of the CEA, is now at the early stages in France. The project implements the direct oxidation process with conversion to PuO_2 and powder mixture.

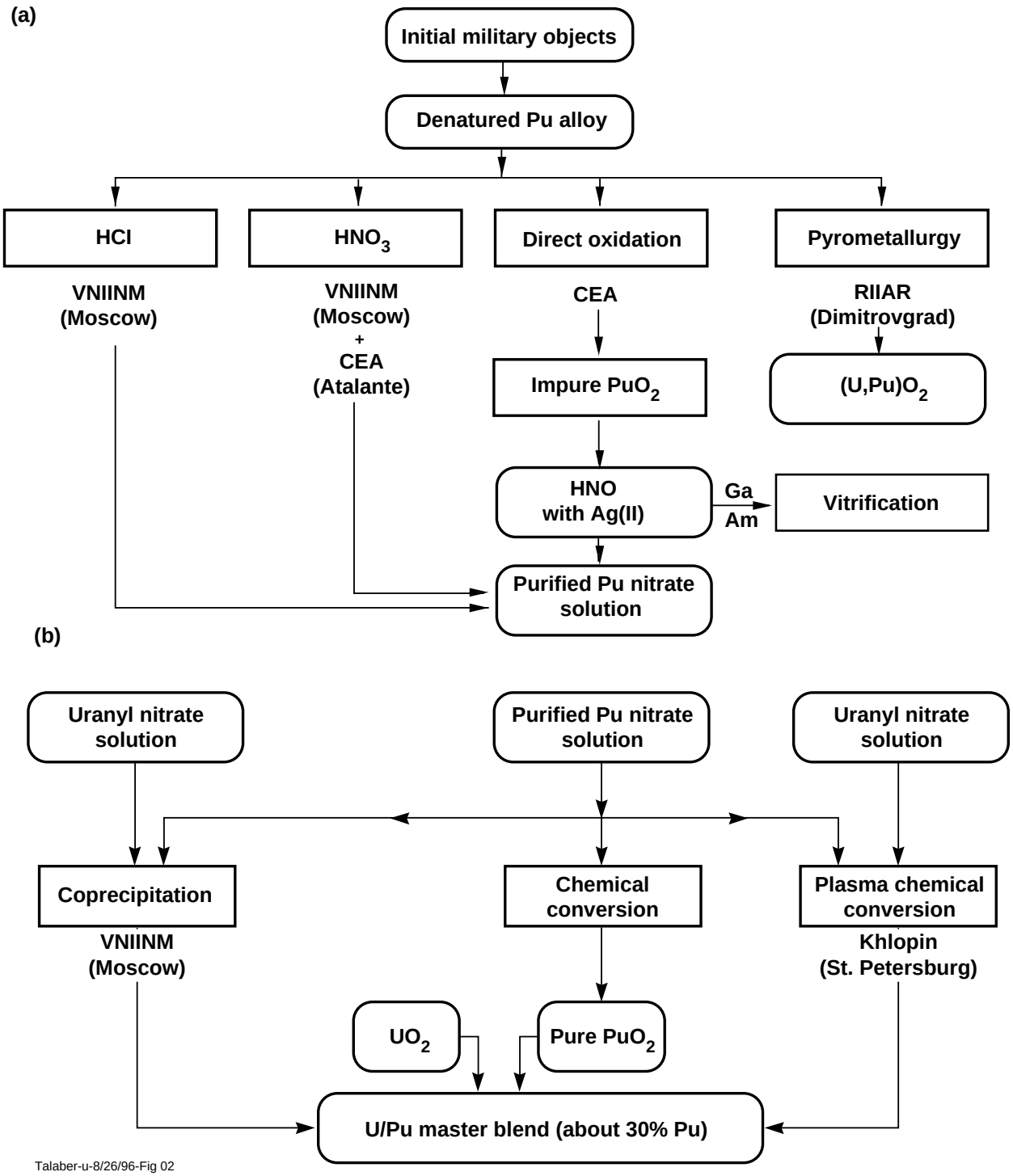

Figure 1. Transformation of weapons-grade plutonium into (a) purified Pu nitrate solution; (b) U/Pu master blend (about 30% Pu).

Conclusion and Outlook

The Franco-Russian feasibility report on the use of plutonium from dismantled Russian warheads to generate electric power for civil applications in Russia, scheduled for release in late 1996, will no doubt open promising prospects for the near future.

In the short term, the use of existing Russian reactors (i.e. BN 600 and four VVER 1000 models) would require a specialized facility such as TOMOX, with an annual capacity of some 1300 kg of weapons plutonium to fabricate approximately 1.5 ton of MOX fuel for the BN 600, and 20 tons of MOX fuel for the VVER 1000 reactors.

I shall just add as a personal conclusion that according to IPPE's (Obninsk) and Minatom's opinions—though they do not reject the necessity of useful utilization of weapons-grade plutonium in reactors—the priority should be given to recycled civil grade plutonium that amounts today to about a 30 ton stockpile to be used in MOX fuel; afterwards one can also burn weapons-grade plutonium. Maybe a combined option will be taken. This will be verified in the frame of the joint Russian/French program. However we are decided to hold to our position, that is a useful civil utilization of civil grade as well as weapons-grade plutonium as a rich energetical resource and as product of large national expenses.

My opinion is that this will be indeed guarantee of non-proliferation, a real measure to protect the environment and a good use of universal wealth. This agrees well with yesterday's overview of M. Kratzer presented on behalf of the American Nuclear Society Special Panel.

Utilization of plutonium in Russia will be most successful in the case the Russian scientists and-technicians are helped within the frame of common efforts with European experts.

An international collaboration, experiences put together are guaranties of safety, security, economics and optimum decisions.

Appendix

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